The effects of turbulence on galactic nuclear gas rings

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ABSTRACT
The gas dynamics in the inner few kiloparsecs of barred galaxies often result in configurations that give rise to nuclear gas rings. A long-standing question is the relationship between the gas dynamics on few-kpc scales and gas transport to the inner few hundred pc. Here we compare hydrodynamic simulations of gas in two different galactic barred potentials out to a radius of 2 kpc. We include self-gravity and a large-scale turbulence driving module. Our aim is to study how the formation of gaseous nuclear rings is affected by changing the gravitational potential, the bar pattern speed, and the strength of the turbulence. The former two effects have been discussed in the literature; we use two different gravitational potentials that represent the inner few kpc of the Galaxy, and two values for the bar pattern speed (40 and 63 km s⁻¹ kpc⁻¹). The simulations show that our turbulence method produces smaller nuclear rings and enhances gas migration towards the inner few pc of the Galaxy, compared to the simulations without turbulence. We also find that a bar pattern speed of 63 km s⁻¹ kpc⁻¹, in concurrence with a large turbulent energy injection, yields results that are consistent with 1) measurements of the inclination of the bar with respect to the line of sight, and 2) observed line-of-sight velocity signatures of the Central Molecular Zone.

1 INTRODUCTION
The main gaseous feature of the Galactic Center (GC) - the Central Molecular Zone (CMZ), has a rich and complex structure that extends over a galactocentric radius of ~500 pc and contains a mass of $M \sim 3 \times 10^6 M_\odot$ (Morris & Serabyn 1996). The densest and most massive part of this region is comprised of a gaseous ring of radius ~100–150 pc (the CMZ ring, Molinari et al. 2011; Kruĳf et al. 2015; Henshaw et al. 2016).

Such gaseous rings are a common morphological feature of barred galaxies. Stellar bars introduce non-axisymmetric torques which produce morphological substructures in the gaseous medium, such as a pair of dust lanes at the leading side of the bar, and a nuclear gaseous ring near the center (e.g., Sanders & Huntley 1976; Roberts et al. 1979; Athanassoula 1992; Buta & Combes 1996; Martini et al. 2003a,b). These nuclear rings can serve as a gas reservoir for the accretion disk that surrounds the supermassive black hole (SMBH) that is present at the centre of most galaxies.

Similarly, the CMZ is believed to be created and fed from the outside by the Galactic bar. According to the most widely accepted theory of galactic dynamics, the gas initially settles into $X_1$ orbits, which occur between the corotation radius and the inner Lindblad resonance (ILR) of the bar potential (e.g., Binney et al. 1991). As inwardly migrating gas approaches the ILR, there is an innermost stable $X_1$ orbit inside of which the orbits become self-intersecting. The gas compresses and shocks near the edges of these orbits, loses angular momentum and descends onto $X_2$ orbits, which are closed and elongated orbits that have their long axes oriented perpendicular to the bar (Binney et al. 1991; Athanassoula 1992; Jenkins & Binney 1994; Gerhard 1996). The shocks along the innermost $X_1$ orbit are presumed responsible for compressing the gas into molecular form, and the accumulated molecular gas on $X_2$ orbits comprises the observed CMZ (e.g., Binney et al. 1991). However, it is unclear how fast molecular gas is transported further in toward the central few parsecs, and which mechanisms are responsible for its transport.

The generic dynamical description of the formation of a gaseous nuclear ring does not take into account the effects of thermal pressure. For example, Patsis & Athanassoula (2000); Kim et al. (2012); Sormani et al. (2015a) and Sormani et al. (2018), showed that, for a given underlying gravitational potential, the size and morphology of nuclear rings depend on the sound speed ($c_s$). Furthermore, it has been shown that the size and location of nuclear rings are also loosely related to the location of the ILR, and thus to the bar pattern speed, although the predicted location is more accurate for strongly barred potentials (e.g., Buta & Combes 1996; Sormani et al. 2015b, 2018).

The relatively high gas temperatures (70-100 K) are one of the key properties of CMZ clouds, and there is evidence showing that the gas is kept warm by the dissipation of turbulence (Immer et al. 2016; Ginsburg et al. 2016). Furthermore, the large turbulent velocity dispersion within the CMZ must be responsible for supporting the gas against gravita-
tional collapse, since the thermal pressure of the gas would be insufficient. This motivates the need to balance the effects of self-gravity. Generally, the effects of turbulence on galaxy simulations have been investigated by using momentum and energy injection from supernova (SN) explosions, which are known to drive turbulence in the interstellar medium (ISM, e.g., Norman & Ferrara 1996; Mac Low & Klessen 2004; Joung & Mac Low 2006). However, we take a different approach from previous studies by driving the turbulence via a Fourier forcing module, based on the methods by Stone et al. (1998) and Mac Low (1999). The details of this method are described in Salas et al. (2019).

In this work we perform simulations of gas residing in the central few kiloparsecs of our Galaxy, using 3D smoothed-particle hydrodynamics (SPH). Our main goal is to investigate the effects of varying the potential and bar pattern speed, as well as the strength of turbulence, on the formation of gaseous nuclear rings. Our investigation includes 1) two gravitational potentials appropriate for a Milky Way like-galaxy, 2) self-gravity and 3) turbulence driving. This paper is organized as follows: we briefly describe our numerical methods in Section 2. We describe our main results in Section 3 and compare them with observations of the CMZ. In Section 4, we discuss our results and approximations, as well as possible improvements for future work, and we conclude with Section 5.

2 NUMERICAL METHODS

2.1 SPH code

We used the N-body/SPH code Gadget2 (Springel 2005), which is based on the tree-Particle Mesh method for computing gravitational forces and on the SPH method for solving the Euler equations of hydrodynamics. The smoothing length of each particle in the gas is fully adaptive down to a length of each particle in the gas is fully adaptive down to a length of each particle in the gas is fully adaptive down to a

\[ \Phi(r, \theta, \phi) = 4\pi G \rho_0 \left( \frac{r}{r_0} \right)^{\alpha} P(\theta, \phi) , \]

where \((r, \theta, \phi)\) are spherical coordinates fixed on the rotating bar, with the supermassive black hole at \(r = 0\), and \(P(\theta, \phi)\) is the associated Legendre function, which can be written as:

\[ P(\theta, \phi) = \frac{1}{(1 + \alpha)} - \frac{Y(\theta, \phi)}{(2 - \alpha)(3 + \alpha)} . \]

\(Y\) is a linear combination of spherical harmonic functions of the \(l = 2, m = 0, 2 \) modes:

\[ Y(\theta, \phi) = -b_20 P_{20}(\cos \theta) + b_{22} P_{22}(\cos \theta) \cos 2\phi . \]

The parameter \(b_{20}\) determines the degree of oblateness/prolateness while \(b_{22}\) determines the degree of non-axisymmetry. Based on previous work by Kim et al. (2011), and most recently by Gallego & Cuadra (2017)\(^1\), we use the parameters: \(\alpha = 0.25, b_{20} = 0.3, b_{22} = 0.1, \rho_0 = 40 \, M_\odot \, \text{pc}^{-3}\) and \(r_0 = 100 \, \text{pc}\). Given these parameters, a bar with axis ratio of \([1: 0.74: 0.65]\) is obtained for the isodensity surface that intersects points \([x = 0, y = \pm 200 \, \text{pc}, z = 0]\). Enclosed masses inside 200 pc and 1000 pc are \(10^9 \, M_\odot\) and \(7 \times 10^9 \, M_\odot\), respectively.

2.2 The galactic potential

The gas dynamics in the inner part of the Galaxy have been studied extensively in the literature using numerical simulations. However, there isn’t a definitive gravitational potential for the inner few kpc of the Milky Way. We describe below the two different potentials we use in order to examine the differences between the resulting nuclear rings.

2.2.1 Potential A

The first gravitational potential we use is adopted from Zhao et al. (1994), which they constructed based on the prolate bar potential introduced by Binney et al. (1991). This potential assumes a power law density distribution for the inner few kpcs of the Galaxy, with the following form:

\[ (\Phi(r, \theta, \phi) = 4\pi G \rho_0 \left( \frac{r}{r_0} \right)^{\alpha} P(\theta, \phi) , \]

where \((r, \theta, \phi)\) are spherical coordinates fixed on the rotating bar, with the supermassive black hole at \(r = 0\), and \(P(\theta, \phi)\) is the associated Legendre function, which can be written as:

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2.2.2 Potential B

The second gravitational potential we use was constructed following a method similar to that adopted by Krumholz & Kurijsjen (2015). Rather than assuming a functional form for the density/potential of the inner Galaxy (as was done for Potential A), they constructed a potential using observations of the Galaxy’s mass distribution and rotation curve. We expect this method to yield a more “realistic” gravitational potential.

For this potential we combined two data sets for the Galaxy’s mass distribution and rotation curve. The first data set is the enclosed mass versus galactocentric radius \(r\) measured by Laurnhardt et al. (2002) at \(r = 0.63 - 488\) pc. The second data set is the rotation curve data compiled by Bhattacharjee et al. (2014) from \(r = 190 - 1.9 \times 10^7\) pc.

We use these tabulated data to fit a single function for the enclosed mass as a function of radius, \(M(r)\) (see Appendix A). However, this function implies spherical symmetry. In order to mimic a bar potential, we make the transformation

\[ r \equiv x + \frac{y}{q_b} + \frac{z}{q_b} . \]

We use \(q_b = 0.63\) as adopted by Kurijsjen et al. (2015), and \(q_b = 0.74\), taken from the \(y\) flattening parameter from the potential described in Section 2.2.1. Accelerations in the \(x, y,\) and \(z\) directions are then computed from:

\[ a_x = -\frac{G M(r)}{r^2} \hat{x} . \]

\(^{1}\) We note that there is a negative sign misprint in Kim et al. (2011) (their Equation 2) and Gallego & Cuadra (2017) (their associated Legendre function).
with $r$ defined as in Equation 4 and the unit vectors
\[
\hat{x} = \frac{x}{\sqrt{x^2 + y^2 + z^2}},
\]
\[
\hat{y} = \frac{y}{q_y \sqrt{x^2 + y^2 + z^2}},
\]
\[
\hat{z} = \frac{z}{q_z \sqrt{x^2 + y^2 + z^2}}.
\]

We note that this method assumes that the gravitational forces at a given radius are due only to mass internal to that radius, which is strictly correct only in spherical symmetry. However, our goal is to qualitatively examine the evolution of the gas and compare the results between the two potentials described in this Section. Thus, this approximation should be sufficient for that purpose.

Figure 1 shows the rotation curve of both potentials, shown as $\Omega - \kappa/2$, where $\Omega = v_\phi / r$ is the angular velocity, $v_\phi$ is the rotation speed, $r$ is the galactocentric radius, and $\kappa = \sqrt{2(1 + \beta)}\Omega$ is the epicyclic frequency, and where $\beta$ is defined as
\[
\beta = \frac{d \ln v_\phi}{d \ln r}.
\]

Potential A is shown as solid (green and black) lines, and Potential B is shown as dashed (green and black) lines. The horizontal red and blue lines indicate the bar pattern speeds we assume in this work (see Section 2.2.3).

2.2.3 Bar pattern speed

In addition to the gravitational force due to the potentials above, we performed the computation in a reference frame rotating with the bar, and therefore included centrifugal and Coriolis forces. We compare two different values for the bar pattern speed: a “fast” bar with $\Omega_{\text{bar}} = 63$ km s$^{-1}$ kpc$^{-1}$, which has been adopted by previous studies (e.g., Kim et al. 2011; Sormani et al. 2015a; Krumholz & Kruijssen 2015), and a “slow” bar with $\Omega_{\text{bar}} = 40$ km s$^{-1}$ kpc$^{-1}$, which is the most recent estimate of the pattern speed of the Galactic bar (Bland-Hawthorn & Gerhard 2016; Portail et al. 2017).

2.3 Turbulence Driving

Supersonic turbulence occurs over a wide range of length scales in the interstellar medium, especially within molecular clouds. The importance of turbulence in modulating star formation in the interstellar medium was further highlighted recently by a combination of numerical and analytical studies (e.g., Krumholz & McKee 2005; Burkhardt 2018). Furthermore, turbulence in the CMZ seems to greatly influence its thermal structure and star formation rate (e.g., Kruijssen et al. 2014).

Numerical simulations have shown that turbulence decays quickly, within a few dynamical timescales (e.g., Stone et al. 1998; Mac Low 1999). Since observations indicate high turbulent velocity dispersions in the CMZ clouds (Morris & Serabyn 1996), turbulence then must be driven by some physical stirring mechanism, e.g., magnetic fields, secular gas instabilities, feedback ejecta, etc. However, the main driving mechanism for turbulence in the CMZ has not yet been definitively identified (see Kruijssen et al. (2014) for a discussion of possible sources of turbulence).

Simulations of turbulence-driven gas are often employed in studies of the interstellar medium and star formation (e.g., Stone et al. 1998; Mac Low et al. 1998; Krumholz & McKee 2005; Burkhart et al. 2009; Federrath et al. 2010). Typically, this is achieved by a Fourier forcing module, which can be modelled with a spatially static pattern in which the amplitude is adjusted in time (Stone et al. 1998; Mac Low 1999). Other studies employ a forcing module that can vary both in time and space (e.g., Padoan et al. 2004; Schmidt et al. 2006; Federrath et al. 2010).

In the case of galaxy simulations, driven turbulence is mimicked by injecting energy due to SN. For example, Kim et al. 2011; Emsellem et al. 2015; Shin et al. 2017; Seo et al. 2019; Armillotta et al. 2019, and Tress et al. 2020 have modelled turbulence by using star formation and SN feedback models. In general, these models depend on underlying assumptions regarding star formation rates, SN energies and injection rates. Furthermore, recent studies (e.g., Scannapieco et al. 2012; Rosdahl et al. 2017; Keller & Kruijssen 2020) have demonstrated that the different choices of SN feedback model (including the underlying physical processes driving the feedback) produce significant differences in morphology, density, etc, of the simulated galaxies.
In order to avoid relying on a particular physical mechanism, we adopt a Fourier forcing module, which has the advantage of being independent of the source of turbulence. Our turbulence treatment is based on the method described by Mac Low (1999), in which a turbulent velocity field is drawn from a spatially static pattern having a power spectrum \( P(k) \propto k^{-n} \), where \( k \) is the wavenumber.

We describe this turbulence model, as well as the performance tests conducted to show its effectiveness, in more detail in Salas et al. (2019). For clarity, we summarize the key factors of the algorithm here. We create a library of ten spatially static turbulent velocity fields (in the form of cubic lattices). Each lattice is created using fast Fourier transforms inside a 128\(^3\) box, resulting in a realization of a turbulent velocity field with power spectrum \( P(k) \propto k^{-4} \). We fill the volume of our simulation domain (4 kpc per side) with 64\(^3\) cubic lattices, each drawn randomly from our library. Each lattice is given a physical size of 64 pc per side. Thus, turbulence is driven at scales of 64/2 = 32 pc to 64/128 = 0.5 pc. We use tri-linear interpolation to calculate the velocity “kicks” given to every gas particle inside each lattice. The amplitude of the velocity kicks is adjusted in time to maintain a constant energy input. Finally, all of the turbulent lattices are changed randomly every time the driving is performed.

Our turbulence implementation contains two free parameters: \( E_{\text{turb}} \), the total energy input per injection, and \( N_t \), the number of timesteps between velocity “kicks” (the timestep is fixed in all simulations to be equal to 1000 yrs). In Salas et al. (2019), we demonstrate that our turbulence module produces consistent results in the range \( E_{\text{turb}} = 10^{46} \text{--} 10^{50} \text{ergs} \), which corresponds to \( \sim 0.01 \text{--} 100\% \) of the thermal energy of the system. We also show that \( N_t \) must be relatively low \((N_t = 2\text{--}5)\) in order to counteract the self-gravity of the high-density gas, due to its fast free-fall time \((t_{ff} \sim 1/\sqrt{G\rho})\). In the present work, however, we expect the density of our large-scale simulations to be much lower than those we studied in Salas et al. (2019) (and thus a larger \( t_{ff} \)), which allows us to consider larger values for \( N_t \).

Here, we simulate two extremes, namely a “low turbulence” model and a “high turbulence” model. This is achieved by tuning the two free parameters, \( E_{\text{turb}} \) and \( N_t \). For simplicity, we fix \( E_{\text{turb}} \) to be \( 10^{47} \text{ergs} \), and use two values for \( N_t = 100 \) and 2, which represent the low and high turbulence models, respectively. We expect the turbulence parameters in the real CMZ to fall between these two extremes.

### 2.4 Initial conditions

We created a gas disk of outer radius 2 kpc, an inner radius of 30 pc, and a Gaussian scale height of 50 pc. The disk contains a total mass of \( 10^8 \text{ M}_\odot \), with each SPH particle having a mass of \( 130 \text{ M}_\odot \). The particles are initially in circular orbits, with their velocities calculated using the potentials described in Section 2.2. All simulations were run using an isothermal equation of state with \( T = 100 \text{ K} \).

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| Model name | Potential | Turbulence | Pattern speed (km s\(^{-1}\) kpc\(^{-1}\)) |
|------------|-----------|------------|------------------------------------------|
| SB-A       | A         | –          | 40                                       |
| SBLT-A     | A         | Low        | 40                                       |
| SBHT-A     | A         | High       | 40                                       |
| FB-A       | A         | –          | 63                                       |
| FBLT-A     | A         | Low        | 63                                       |
| FBHT-A     | A         | High       | 63                                       |
| SB-B       | B         | –          | 40                                       |
| SBLT-B     | B         | Low        | 40                                       |
| SBHT-B     | B         | High       | 40                                       |
| FB-B       | B         | –          | 63                                       |
| FBLT-B     | B         | Low        | 63                                       |
| FBHT-B     | B         | High       | 63                                       |

Table 1. Summary of all models. SB and FB stand for “slow bar” and “fast bar”, respectively. HT and LT stand for “high turbulence” and “low turbulence”, respectively. The low turbulence models correspond to injecting \( E_{\text{turb}} = 10^{47} \text{ergs} \) of energy every \( N_t = 100 \) timesteps, and the high turbulence models correspond to \( E_{\text{turb}} = 10^{47} \text{ergs} \) of energy every \( N_t = 2 \) timesteps (see Section 2.3).

### 3 RESULTS

We performed a total of 12 simulations, six of them using each of the gravitational potentials described in Sections 2.2.1 and 2.2.2. For both potentials, we use the slow and fast bar pattern speed values described in Section 2.2.3, and the low and high turbulence parameters described in Section 2.3. To save computational time, the simulations ran for 200 Myrs, which should be long enough for the gas to reach a semi-steady state. We also performed four simulations with no turbulence (and no self-gravity), using both potentials, each with a slow and fast bar, for comparison. Table 1 summarizes each model.

#### 3.1 Comparison with previous work

Figure 2 shows the final state of the gas at \( t = 200 \text{ Myrs} \) for all simulations performed with both potentials. This is a representative example as all simulation reached steady state by \( \sim 150 \text{ Myrs} \). In all simulations, the gas accumulates on \( x_2 \) orbits, forming an elongated ring, as expected.

As mentioned in previous work (e.g., Sormani et al. 2015c), varying the bar pattern speed dictates the location of the nuclear ring. The size of a nuclear ring is related to the radius of the ILR (Buta & Combes 1996; Sormani et al. 2018): increasing the pattern speed pushes the ILR inward, as can be seen in Figure 1. Thus, the smallest nuclear rings in our runs were produced by the fast bar models in both potentials.

Furthermore, our turbulence treatment introduces structure to the nuclear rings compared to the runs without turbulence. In Figure 3 we show a zoom-in of the inner
Figure 2. Top: face-on view of Potential A simulations at $t = 200$ Myrs. Bottom: Potential B simulations at $t = 200$ Myrs. In all runs, slow-bar models produce a bigger ring than the fast-bar models. Furthermore, the high turbulence models make the nuclear rings thicker. Long axis of the bar lies along the $x$-axis.
Figure 3. Face-on view of Potential A and Potential B simulations at $t = 200$ Myrs, zoomed-in to the inner 1600 pc. Long axis of the bar lies along the x-axis.
Figure 4. Position-velocity diagrams of turbulence simulations with Potential A (the major axis of the Galactic bar is inclined at an angle of 30° with respect to the line of sight). Blue circles represent data from Figure 9 (bottom panel) in Henshaw et al. (2016). The fast-bar/high-turbulence model aligns best with the data.

800×800 pc of the simulations. The high turbulence models make the nuclear rings smaller and thicker than the low turbulence models. For a given gravitational potential, simulations with a fast bar and high turbulence (FBHT) produce a nuclear ring that is completely filled and smaller than all other models. This effect has been explored by Kim et al. (2012) and later by Sormani et al. (2015a, 2018), who demonstrated that nuclear rings shrink in size with increasing sound speed ($c_s$). Our simulations are isothermal, which means the sound speed is unchanged. However, the injected turbulence contributes an additional velocity dispersion, effectively increasing the sound speed and thus accounting for the shrinking of the nuclear ring. Furthermore, Tress et al. (2020) demonstrate that SN feedback (as well as torques from self-gravity) also influences inflow from the CMZ to the central region. Our turbulence method captures these effects, which help drive gas from the nuclear ring to the inner few pc.

3.2 Comparison with CMZ observations

3.2.1 Mass and size

Recent studies have shown that the gas in the inner part of the CMZ is approximately composed of a ∼ 100-150 pc-radius stream of molecular gas on an elongated orbit (Molinaro et al. 2011; Kruijssen et al. 2015; Henshaw et al. 2016). Here we find that, while the slow bar models produce nuclear rings that are too big to resemble the observed CMZ
Figure 5. Position-velocity diagrams of turbulence simulations with Potential B (the major axis of the Galactic bar is inclined at an angle of 30° with respect to the line of sight). Blue circles represent data from Figure 9 (bottom panel) in Henshaw et al. (2016). The fast-bar/high-turbulence model aligns best with the data.

The smallest nuclear ring among all simulations was produced by the FBHT-A model, which gave rise to a ∼200 pc radius ring (on its short axis). This is only slightly bigger than the observed CMZ ring. The FBHT-B model produced a similar ring (∼250 pc on its short axis).

In addition, there are mass similarities between our simulations and the CMZ ring. The slow bar models give rise to nuclear rings of mass ∼4.6 × 10^7 M_⊙ and ∼7.5 × 10^7 M_⊙ for Potentials A and B, respectively. Meanwhile, the fast-bar produce rings with mass ∼1.4 × 10^7 M_⊙ and ∼2.5 × 10^7 M_⊙ for people Potentials A and B, respectively. In contrast, the mass of the CMZ ring has been observationally estimated to be ∼3 × 10^7 M_⊙ (Molinari et al. 2011). Given this comparison between masses and sizes of our models with the real CMZ, our simulations seem to favor Potential B, with a fast pattern speed value of Ω_{bar} = 63 km s^{-1} kpc^{-1}.

3.2.2 Line-of-sight velocity

To further quantify the comparison with observations we examine the line-of-sight velocity of these structures. Figure 4 shows position-velocity diagrams for all four Potential A turbulence simulations, while Figure 5 shows position-velocity diagrams for all four Potential B turbulence simulations. The diagrams were computed with the major axis of the Galactic
bar inclined 30° with respect to the line of sight. Also, we assumed a distance to the Galactic Center of 8 kpc.

We compare these diagrams with observations of the CMZ by Henshaw et al. (2016): a sequence of data points was extracted from their Figure 9 and drawn as semi-transparent blue circles in Figures 4 and 5. The FBHT models in both potentials show the best match with the noticeable slope of the CMZ’s position-velocity data (lower left diagram in Figures 4 and 5). This is expected since the data represented by the blue circles correspond to fast-moving gas within the ∼100-pc ring. While all simulations contain particles at this radius (cf. Figure 3), the slow bar runs (and the fast bar/low turbulence runs) contain most of their mass (i.e., particles) outside the range of the position-velocity diagrams, and gas is slower moving at larger radii, hence the shallower slope. Only the FBHT models in both potentials contain a significant amount of particles at r ∼ 100-150 pc.

It is worth examining how the position-velocity diagrams would change with different bar inclinations. Among all simulations, the FBHT models match best with observations. Thus, we show in Figures 6 and 7 the position-velocity diagrams for the FBHT-A and FBHT-B models at different bar inclinations with respect to the line of sight (15°, 25°, 35° and 45°). Qualitatively, bar inclinations greater than 25° provide a better match to the data from Henshaw et al. (2016), and this range is also consistent with the bar inclination range suggested by Wegg et al. (2015).

4 DISCUSSION

The complex gas dynamics in the CMZ is dictated mainly by the underlying potential of the Galaxy. Here, we have not only investigated the effects of two different potentials but also included the effects of turbulence. The effects of the potential and bar have been investigated previously in the literature in the context of the kinematic theory of galactic dynamics, and our simulations are indeed in agreement with those (Binney et al. 1991; Athanassoula 1992; Jenkins & Binney 1994; Gerhard 1996). We demonstrated that our key additional physical process, turbulence, further alters the morphology of the CMZ (Figures 2 and 3). In this section, we offer a discussion of our results and their comparison with observations.

In general, the sizes of nuclear rings are controlled by: 1) the strength of the galactic bar, 2) the bar pattern speed, and 3) the sound speed (see Sormani et al. 2019, and references therein). In this work we find that, by comparing with observations, our simulations can be used to differentiate between the two suggested potentials, the speed of the bar, and the bar’s inclination with the line of sight.

4.1 Comparison between Potentials A and B

Potential A (Zhao et al. 1994) was constructed from the simplifying assumption that the density distribution of the Galaxy obeys a power law. Potential B was constructed using observational data from the Galaxy’s rotation curve (Launhardt et al. 2002; Bhattacharjee et al. 2014). As mentioned in the previous section, both potentials give similar results. However, we expect Potential B to be closer to reality than Potential A. The smallest nuclear ring among all simulations was produced by the FBHT-A model, which gives rise to a ring with a ∼200 pc radius (on its short axis) and a mass of 1.4 × 10^7 M☉. This is slightly larger and less massive than what observations indicate. On the other hand, the slow bar models (with potential A) produced rings with masses consistent with observations, but are even larger than the FBHT-A ring.

In comparison, the Potential B simulations produced slightly larger and more massive rings than those produced by Potential A. The FBHT-B model produced the smallest ring out of all Potential B models (∼250 pc radius on its short axis), and its mass is relatively similar to observations (2.5 × 10^7 M☉), which is expected due to its larger size than the FBHT-A ring.

When comparing our models to data from Henshaw et al. (2016), we find that our simulations agree best with the observations when using a “fast” pattern speed of Ωp = 63 km s⁻¹ kpc⁻¹. In contrast, some studies have constrained the Milky Way’s bar pattern speed to be comparable to our slow bar models, i.e., Ωp = 40 km s⁻¹ kpc⁻¹ (Bland-Hawthorn & Gerhard 2016; Portail et al. 2017). Furthermore, none of the produced rings in any of the simulations exactly resemble the size and morphology of the observed CMZ ring (Molinari et al. 2011; Kruijssen et al. 2015; Henshaw et al. 2016). These discrepancies are rooted in the underlying potential. Although the true gravitational potential of our Galaxy remains somewhat uncertain, we have in this paper attempted to construct a realistic potential using observational data. However, there are relatively few data points in the 200-1000 pc range from the Bhattacharjee et al. (2014) data set (see Appendix A). In our fit, we ignore these data points, since they also conflict with the mass measurements by Launhardt et al. (2002). To better match our simulations with observations, we would need more accurate measurements in this range. Such exploration is left for future work.

We note that in the low-turbulence models of Potential B, a smaller, less massive ring (5 × 10^7 M☉) is formed inside the larger, more massive ring (see Figure 3). These smaller rings are located at a radius of ∼100 pc, which matches the location of the CMZ ring in our Galaxy. This seems to be a natural consequence of the shape of the rotation curve, as described below in Section 4.2.

4.2 Shear minimum

The mass distribution observations of Launhardt et al. (2002) are the most accurate available for the inner 500 pc of the Milky Way. A previous study by Krumholz & Kruijssen (2015) used this mass distribution to develop a dynamical model for the formation of the CMZ ring. Gas is transported to the CMZ ring via angular momentum transport induced by acoustic instabilities within the bar’s ILR. According to their model, this process can drive turbulence within the gas and temporarily keeps it gravitationally stable. At some point the rotation curve must transition from approximately flat at large radii to approximately solid body near the center. This results in a minimum in the local shear.
which reduces this inward flow and causes gas to build up at the radius of the shear minimum. The dimensionless rate of shear is given by $1 - \beta$, where $\beta$ is defined in Equation 11.

In the top panel of Figure 8 we use the mass distribution measured by Launhardt et al. (2002) (Potential B) to display the shear as function of radius (dashed line), and we compare it to the shear of the potential by Zhao et al. (1994) (Potential A, solid line). The location of the minimum shear in Figure 8 is found to be near $r \sim 100$ pc, which corresponds to the location of the observed CMZ ring (Molinari et al. 2011; Henshaw et al. 2016). This shear minimum is the likely explanation for the small 100 pc rings in the Potential B, low turbulence simulations. The dynamical model by Krumholz & Kruijssen (2015) also produced a gaseous ring at this radius.

Therefore, according to Krumholz & Kruijssen (2015), the location of minimum local shear is also important in determining the location of nuclear rings. In the CMZ, this occurs at a galactocentric radius of $\sim 100$ pc, according to Launhardt et al. (2002) (as shown in the top panel of Figure 8). This is a natural consequence of the shape of our Galaxy’s rotation curve. We compare the rotation curves from this work and the data by Launhardt et al. (2002) in the bottom panel of Figure 8 (see also Figure 1).

Figure 8 (top panel) also shows that Potential A (see Section 2.2, Equation 1) has no minimum shear in the region

Figure 6. Position-velocity diagrams for the fast bar/high turbulence model with Potential A (FBHT-A). Only particles in the range $80 \text{ pc} < r < 120$ pc are shown. Each panel represents a different angle of the bar’s major axis with the line of sight: Top left: $15^\circ$, Top right: $25^\circ$, Lower left: $35^\circ$, Lower right: $45^\circ$. Blue circles represent data from Figure 9 (bottom panel) in Henshaw et al. (2016). Qualitatively, bar inclinations greater than $25^\circ$ provide the best match to the data, and this range is also consistent with the observations of Wegg et al. (2015), which were used to deduce a bar inclination of $28^\circ - 33^\circ$.
Figure 7. Position-velocity diagrams for the fast bar/high turbulence model with Potential B (FBHT-B). Only particles in the range 80 pc < r < 120 pc are shown. Each panel represents a different angle of the bar’s major axis with the line of sight: Top left: 15°, Top right: 25°, Lower left: 35°, Lower right: 45°. Blue circles represent data from Figure 9 (bottom panel) in Henshaw et al. (2016). Qualitatively, bar inclinations greater than 25° provide the best match to the data.

$r < 500$ pc. This is expected given the power-law dependence of Potential A, which produces a constant value of $\beta$. In our work, we find nuclear rings in both potentials, regardless of the minimum shear locations. Thus, the existence of a shear minimum in the rotation curve does not seem to be a requirement for the formation of nuclear rings. This was also shown by Sormani & Li (2020).

4.3 Turbulence

The qualitative differences between the runs with and without turbulence are apparent in Figures 2 and 3. As mentioned in Section 3, our turbulence treatment creates smaller and thicker rings than the no-turbulence models. The creation of smaller and thicker rings was previously shown to depend on the speed of sound (e.g., Kim et al. 2012; Sormani et al. 2015a, 2018). In particular, the nuclear rings shrink in size with increasing sound speed. Our turbulence method effectively increases the speed of sound, thus creating a smaller and thicker ring. Also, we find that for a given bar pattern speed, our turbulence driving module does not significantly affect the mass of the resulting nuclear rings.

Both FBHT simulations with potentials A and B have rings that are completely filled in. This is because, as seen in the literature, turbulence enhances inflow rates towards supermassive black holes (SMBHs). For example, simulations by Tress et al. (2020) showed that SN feedback, as well as torques from self-gravity, drive gas from the CMZ...
Figure 8. Top: the dimensionless shear $1 - \beta$ (see Equation 11) as a function of radius. The solid line indicates the shear derived from Potential A used in this paper, described in Section 2.2 (and in Kim et al. 2011). The dashed line indicates the shear calculated from the mass distribution data of Launhardt et al. (2002), which indicates a local minimum at $r \sim 100$ pc. Bottom: angular frequencies versus radius for both the Launhardt et al. data (dashed green and black lines) and the Zhao et al. (solid green and black lines) potentials. For comparison, we also show the “fast” and “slow” bar models we used in this work (solid red and blue lines, respectively).

to the central few pc. This is because stellar feedback associated with episodes of star formation activity in the CMZ can stochastically launch parcels of gas towards the center (e.g., Davies et al. 2007). Similarly, other authors have suggested that SN feedback and supersonic turbulence inside accretion disks (e.g., Wang et al. 2009) can promote accretion onto SMBHs by enhancing angular momentum transfer (e.g., Collin & Zahn 2008; Chen et al. 2009).

Finally, it is worth noting that the ring produced by the FBHT-A model is similar, in terms of shape and mass, to that of Kim et al. (2011) (cf. their Figure 1). This is not entirely surprising since this model uses the same gravitational potential, the same value for the bar pattern speed, and same initial mass of the large-scale disk as in their study. The main difference between the two simulations is the mechanism for turbulence driving. Kim et al. (2011) used a model of stellar feedback in which SN are simulated by injecting thermal energy into surrounding SPH particles. Our turbulence module injects kinetic energy in the form of a velocity field with a $k^{-4}$ power spectrum to all particles.

These comparisons show that our turbulence driving method is comparable to typical methods of SN feedback in driving turbulence. However, turbulence in the Galaxy, and particularly in the CMZ, does not necessarily come only from SN feedback. In fact, the dominant source of turbulence in the CMZ has not been yet conclusively identified (Kruisjes et al. 2014). Turbulence is produced by the interplay of many sources: SN blasts, stellar winds, magnetic fields, gas instabilities, etc., all which work in different scales and combine to create a turbulence spectrum that has been observed in the literature to approximately obey a power law (e.g., Elmegreen & Scalo 2004). Hence, the turbulence injection mechanism used here can account for many sources of turbulence within a given range of scales.

5 CONCLUSIONS

The relative closeness of the Milky Way’s CMZ offers a unique opportunity to study the gas dynamics that probably take place in other galaxies. Here we show, using SPH simulations, that the complex morphological details observed in this regime can be used to disentangle the underlying effects of the speed of the bar and its inclination with respect to the line of sight.

Our conclusions can be summarized as follows:

- When comparing to the observations by Henshaw et al. (2016), our models seem to favor a “fast” bar pattern speed of $\Omega_p = 63$ km s$^{-1}$ kpc$^{-1}$. Our work also suggests a bar inclination greater than $25^\circ$ with respect to the line of sight, which is consistent with observations by Wegg et al. (2015). However, the pattern speed of the Galactic bar has been recently constrained to be consistent with a slower value of $\sim 40$ km s$^{-1}$ kpc$^{-1}$ (e.g., Bland-Hawthorn & Gerhard 2016). The source of this discrepancy lies in the gravitational potential. In this work we constructed a potential using measurements of the Galaxy’s rotation curve. However, these data contain limited information in the $\sim 200 – 1000$ pc range. Future work is needed to find a more accurate potential of the central $1 – 2$ kpc of the Galaxy, which could help to better determine the bar’s rotation speed and resolve discrepancies with observations.

- The turbulence driving method we developed gives results similar to methods based on SN feedback. Moreover, our method has the advantage of being able to account for many different sources of turbulence occurring on a broad range of scales. Due to computational constraints, in this work we focused only on a limited range of injection scales, as well as two limiting cases for the strength of the turbulence injection. A more heuristic exploration of the turbulence parameters and turbulence scales could be performed in the future to better match observations. Our results indicate that our turbulence driving module is a promising way to model turbulence in this complex environment.
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APPENDIX A: FITTING THE POTENTIAL

In Section 2.2.2 we describe the gravitational potential built in a similar approach to Krumholz & Kruijssen (2015). We used two datasets: the mass distribution from Launhardt et al. (2002) and the velocity curve from Bhattacharjee et al. (2014) (which we convert to an enclosed mass).

In Figure A1 we show the data and our fit to them. We note that there is some disagreement between the two data sets in the range 200-500 pc. The dataset from Bhattacharjee et al. (2014) contains only 3 data points in this range, so we ignore them in our fit. The form of our fitted $M(r)$ function is:

$$M(r) = \frac{p_1 x^4 + p_2 x^3 + p_3 x^2 + p_4 x + p_5}{x^3 + q_1 x^2 + q_2 x + q_3}$$  \hfill (A1)

where $x = \log_{10}(r)$, $p_1 = 1.759$, $p_2 = -0.9208$, $p_3 = -0.7878$, $p_4 = -31.87$, $p_5 = 53.95$, $q_1 = -1.9$, $q_2 = -3.441$, $q_3 = 7.373$.

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