Stochastic Noncircular Motion and Outflows Driven by Magnetic Activity in the Galactic Bulge Region

Takeru K. Suzuki$^{1, *}$, Yasuo Fukui$^{1}$, Kazufumi Torii$^{1}$, Mami Machida$^{2,}$, & Ryoji Matsumoto$^{3}$

$^1$Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
$^2$Department of Physics, Faculty of Sciences, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan
$^3$Department of Physics, Graduate School of Science, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

1 May 2015

ABSTRACT

By performing a global magneto-hydrodynamical simulation for the Milky Way with an axisymmetric gravitational potential, we propose that spatially dependent amplification of magnetic fields possibly explains the observed noncircular motion of the gas in the Galactic center region. The radial distribution of the rotation frequency in the bulge region is not monotonic in general. The amplification of the magnetic field is enhanced in regions with stronger differential rotation, because magnetorotational instability and field-line stretching are more effective. The strength of the amplified magnetic field reaches $\sim 0.5$ mG, and radial flows of the gas are excited by the inhomogeneous transport of angular momentum through turbulent magnetic field that is amplified in a spatially dependent manner. In addition, the magnetic pressure-gradient force also drives radial flows in a similar manner. As a result, the simulated position-velocity diagram exhibits a time-dependent asymmetric parallelogram-shape owing to the intermittency of the magnetic turbulence; the present model provides a viable alternative to the bar-potential-driven model for the parallelogram-shape of the central molecular zone. This is a natural extension into the central few 100 pc of the magnetic activity, which is observed as molecular loops at radii from a few 100 pc to 1 kpc. Furthermore, the time-averaged net gas flow is directed outward, whereas the flows are highly time-dependent, which we discuss from a viewpoint of the outflow from the bulge.

Key words: accretion, accretion disks — Galaxy: bulge — Galaxy: center — Galaxy: kinematics and dynamics — magnetohydrodynamics (MHD) — turbulence

1 INTRODUCTION

Observations of the atomic and molecular interstellar medium in the inner Milky Way exhibit large noncircular motion of the gas (Rougoor & Oort 1960; Scoville 1972; Liszt & Burton 1978; Bally et al. 1987; Oka et al. 1998; Tsuboi, Handa & Ukita 1999; Sawada et al. 2004; Oka et al. 2005; Takeuchi et al. 2010). Among various possible explanations for the noncircular motion, de Vaucouleurs (1964) raised a possibility that the gas responds to a stellar bar potential of the Milky Way. Blitz & Spergel (1991) identified a bar-like distribution in the infrared observation by Matsumoto et al. (1982) see also Hayakawa et al. (1981). Based on these consideration and finding, Binney et al. (1991) showed that a bar-like potential naturally reproduces the noncircular motion by comparing observed and calculated $l - v$ (Galactic longitude – line-of-sight velocity from the Local Standard of Rest; LSR, hereafter) diagrams. The streaming motion driven by the bar potential provides an only viable explanation on the parallelogram, which has been explicitly discussed in literatures (Koda & Wada 2002; Rodriguez-Fernandez & Combes 2008; Baba, Saitoh & Wada 2010; Molinari et al. 2011). We however find that the observed parallelogram in the 2.6mm CO emission shows asymmetry in the positive and negative velocities and in $l$, including CO features only at positive longitudes, $l = 3 \text{ degrees}$ (clump 2) and 5.5 degrees (e.g., Balia 1977; Torii et al. 2010b). We also see that the central molecular zone (CMZ, hereafter) shows vertical CO features up to vertical distance $\sim 200 \text{ pc}$ (Enokiya et al. 2014; Torii et al. 2014b), which we further discuss later in this section. We note that these outstanding observed characteristics remain unexplored by the bar potential model.

On the other hand, magnetic field is also supposed to...
play an important role in the Galactic bulge. Complicated structures, e.g., nonthermal filaments, are observed in the Galactic center region, which probably attribute to magnetic fields (Yusef-Zadeh, Morris & Chance 1984; Tsuboi et al. 1986; Chuss et al. 2003; Nishiyama et al. 2010; Morris 2014). Crocker et al. (2010) gave a lower limit on the field strength, > 50 μG, over the central 400 pc region from a non-thermal radio spectrum. By other considerations, it is argued that inferred magnetic field strength there is as strong as ∼ mG (Morris et al. 1992; Ferrière 2009).

If such strong magnetic field is distributed in the bulge, it affects the global gas dynamics there (e.g., Sofue 2007). In fact, Fukui et al. (2006) and see also Fujishita et al. (2009), Torii et al. (2010a,b), Riquelme et al. (2010), Kudo et al. (2011) detected large molecular loops that are triggered by magnetic buoyancy (Parker instability; Parker 1966), while the main focus in Parker (1966) was aimed at the Galactic disk, he already suggested that the magnetic activity might become even more important in the central few 100 pc. These molecular loops are also well reproduced by magnetohydrodynamical (MHD, hereafter) simulations (Machida et al. 2009; Takahashi et al. 2009). Recent observation further reveals CO emission at high Galactic latitude, b, including several filamentary features in addition to diffuse extended halo-like CO gas up to 2 degrees in b above and below the CMZ (Torii et al. 2014b). A plausible interpretation is that these high-b features also are driven by the Parker instability; although they are filamentary without a clear loop-like shape having two foot points, the MHD numerical simulations by Machida et al. (2009) show that magnetic-flotation loops are generally not symmetric and can be seen as an open single filament depending on the ambient density/field distribution and evolutionary effect. Further signature is associated with the double helix nebula (DHN, hereafter) toward (l, b) = (0.0 deg., 0.8 deg.) (Morris, Uchida & Do 2006), where a column of molecular gas of 200-pc height is found to be associated with the DHN which is nearly vertical to the plane (Enokiya et al. 2014; Torii et al. 2014b). Such a feature is explained as created by a magnetic tower formed above and below the central black hole according to the preceding numerical simulations (Kato, Mineshige & Shibata 2004; Machida et al. 2009).

In addition, the importance of magnetic activity in the formation of the Fermi bubbles, which are recently found two gigantic gamma-ray bubbles originating from the Galactic center region (Su, Slatyer & Finkbeiner 2010), is also pointed out (Carretti et al. 2013).

In spite of the broad recognition of the strong magnetic field in the Galactic center, there is little theoretical work that explores the role of the magnetic field in the dynamics of the gas component, except a limited number of attempts (e.g., Machida et al. 2009; Kim & Stone 2012; Machida et al. 2013). We naturally expect that the magnetic field may play an essential role in the noncircular motion of the gas in the Galactic center region, which is the main aim of the present paper.

In this paper, we investigate the evolution and the role of magnetic field in the central region of the Milky Way by a three-dimensional (3D) MHD simulation. We do not take into account a bar potential but an axisymmetric potential to focus on the role of the magnetic field in exciting the noncircular motion of the gas.

Figure 1. Radial profile of the equilibrium initial condition at the midplane. top: Sound speed (dashed) and initial rotation speed (solid) at the midplane. The rotation speed of the stellar component, vrot,⋆ = √(RGM2/Rz) (dotted) is also shown for comparison. Bottom: Initial density (dashed; left axis), gas pressure (solid; right axis), and magnetic pressure, pB = B2/8π (dotted; right axis). pB is multiplied by 1000 times to fit in the panel.

2 SIMULATION SETUP

We treat the evolution of gas by solving MHD equations under an external axisymmetric Galactic gravitational potential. We consider three components of the gravitational sources: The supermassive blackhole (SMBH) at the Galactic center (component i = 1), a stellar bulge (i = 2), and a stellar disk (i = 3). For the SMBH we assume a point mass, M1 = 4.4 × 10⁶M⊙ (Genzel, Eisenhauer & Gillessen 2010), where M⊙ is the solar mass. For the i = 2 and 3 components, we adopt a gravitational potential introduced by Miyamoto & Nagai (1975) for the bulge and disk components. The gravitational potential that includes these three components is written as

$$\Phi(R, z) = \sum_{i=1}^{3} \frac{-GM_i}{\sqrt{R^2 + (a_i + \sqrt{b_i^2 + z^2})^2}}$$

(1)

where R and z are cylindrical radius and vertical distance, respectively, and the adopted values for M₁, a₁, and b₁ are summarized in Table I. a₁ = b₁ = 0 since we assume a point mass for the SMBH, and for the bulge and disk components we use the same values for M₁, a₁, and b₁ in Miyamoto & Nagai (1975) (see also Machida et al. 2009).

Assuming an equation of state for ideal gas, the gas pressure,

$$p = ρc_s^2,$$

(2)

where ρ is gas density and c_s(∞ √T) is sound speed. We consider the spatial dependence of the temperature (∝ c_s^2)
but assume that it is kept constant with time in each grid cell; the gas is assumed to be locally isothermal. Since we treat the Galactic bulge and disk by global simulations, the “sound speed” here more or less reflects the velocity dispersion of gas clouds rather than the actual temperature of each cloud. In the disk region, we assume \( c_s \) is comparable to the observed velocity dispersion (e.g., Bovy et al. 2012).

\[
c_s,\text{disk} = 30 \text{ km s}^{-1},
\]

whereas this value is much smaller than the rotation speed \( \sim 200 \text{ km s}^{-1} \). In the bulge region, however, large velocity dispersion, which is probably because of the noncircular motions, is obtained (e.g., Kent 1992). To mimic this larger velocity dispersion, we adopt

\[
c_s,\text{bulge} = 0.6 c_{\text{rot,⋆}}, \quad \text{where}
\]

where \( c_{\text{rot,⋆}} \) is the rotation speed of the stellar component.

We smoothly connect these two components to fix the radial dependence:

\[
c_s^2 = c_s^2,\text{bulge} \left[ 1 - \tanh \left( \frac{R - R_0}{\Delta R_0} \right) \right] + c_s^2,\text{disk} \left[ 1 + \tanh \left( \frac{R - R_0}{\Delta R_0} \right) \right],
\]

where we assume the boundary between the bulge and the disk, \( R_0 = 1 \text{ kpc} \), with a smoothing width, \( \Delta R_0 = 0.8 \text{ kpc} \).

We start our simulation from an equilibrium configuration, in which the gravity is balanced with the pressure-gradient and centrifugal forces:

\[
-\frac{1}{\rho} \frac{\partial \rho}{\partial R} + R \frac{\partial \Omega^2}{\partial R} = \frac{\partial \Phi}{\partial R} = 0,
\]

and

\[
-\frac{1}{\rho} \frac{\partial \rho}{\partial z} - \frac{\partial \Phi}{\partial z} = 0.
\]

We assume the initial gas density at the midplane is proportional to the stellar density that fixes the gravitational potential, namely \( \rho \propto \frac{\Delta \Phi}{4\pi G} \). Then, we determine the distribution of the initial density and rotation frequency, \( \Omega \), to satisfy Equations (6) and (7).

Figure 1 presents the radial distribution of the initial equilibrium profile at the midplane. The rotation speed of the gas component shows a bump near \( R = 0.5 \text{ kpc} \), associated with a peak of the sound speed there (top panel). In this region, because of the high temperature, the outward pressure-gradient force is not negligible, compared to the centrifugal force; the inward gravity is balanced by both the pressure-gradient force and the centrifugal force. To satisfy this radial force balance, the rotation speed should be kept considerably smaller than the rotation speed of the stellar component there to suppress the centrifugal force. This equilibrium configuration plays an important role in the amplification of the magnetic field as will be discussed later.

The bottom panel of Figure 1 presents the initial density, the gas pressure, and the magnetic pressure. The density is expressed by the number density, \( n \text{ cm}^{-3} = \rho/\mu m_\text{H} \), with mean molecular weight, \( \mu = 1.2 \), where \( m_\text{H} \) is the mass of a hydrogen atom. In this work we adopt the one-fluid approximation and do not distinguish ions, neutral atoms, and molecules. \( n \) with \( \mu = 1.2 \) approximately corresponds to number density in units of hydrogen atoms. For rough estimates of molecular number density, which is dominated by \( H_2 \), in dense clouds, we can use \( n_H \approx 0.5n \). Initially we set up weak vertical magnetic field with,

\[
B_z = 0.71 \mu G \left( \frac{R}{1 \text{ kpc}} \right)^{-1},
\]

in the region of \( R > 0.035 \text{ kpc} \). The initial magnetic pressure, \( p_B = B^2/8\pi \), is less than \( < 10^{-3} \) times the gas pressure as shown in the bottom panel of Figure 1.

We update \( \rho, v, \) and \( B \) with time by solving ideal MHD equations,

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0,
\]

and

\[
\frac{\partial v}{\partial t} = -\rho (v \cdot \nabla) v - \nabla \left( p + \frac{B^2}{8\pi} \right) + \left( \frac{\nabla \Phi}{4\pi} \right) B - \rho \nabla \Phi,
\]

under the fixed gravitational potential (Equation 1). The numerical scheme we adopt is the second-order Godunov-CMoCCT method [Sano, Inutsuka & Miyama 1999], in which we solve nonlinear Riemann problems with magnetic pressure at cell boundaries for compressive waves and adopt the consistent method of characteristics (CMoC) for the evolution of magnetic fields [Clarke 1996 Stone & Norman 1992, under the constrained transport (CT) scheme [Evans & Hawley 1988]]. Since we assume the locally isothermal equation of state (Equation 2), we do not solve an energy equation. We perform our simulation in spherical coordinates, \( (r, \theta, \phi) \), instead of cylindrical coordinate, \( (R, \phi, z) \), to resolve the central region by fine-scale grids. The size of the simulation box and the number of the grid points are summarized in Table 2. The size of the radial grid, \( \Delta r \), is enlarged in proportion to \( r \). We analyze the numerical data mainly in the cylindrical coordinates by converting the primitive data in the spherical coordinates.

We adopt the same boundary condition as in Suzuki & Inutsuka (2014). We prescribe the outgoing condition for both mass and waves at the \( \theta \) boundaries, which was originally developed for simulations for the solar wind (Suzuki & Inutsuka 2005, 2006), and the accretion condition at both the outer and inner \( r \) boundaries. Because of the outgoing

| \( M_\bullet (10^{10} M_\odot) \) | \( a_i (\text{kpc}) \) | \( b_i (\text{kpc}) \) |
|---|---|---|
| SMBH 1 | \( 4.4 \times 10^{-4} \) | 0 | 0 |
| Bulge 2 | 2.05 | 0 | 0.495 |
| Disk 3 | 25.47 | 7.258 | 0.52 |

Table 1. Parameters for the gravitational potential. The parameters for the super-massive black hole (SMBH) are from Genzel, Eisenhauer & Gillessen (2010), and the parameters for the bulge and disk components are from Miyamoto & Nagai (1975).
shear of the initial rotation profile \cite{Suzuki2014, McNally2014} to generate the radial and toroidal components. The toroidal component is further amplified by the winding due to the radial differential rotation. Furthermore, magnetic buoyancy \cite{Parker1966} also plays a role in amplifying the vertical component \cite{Nishikori2006, Machida2006, Machida2013}. Figure 2 presents 3D snapshots of the bulge region, $R < 1$ kpc, after the MHD turbulence is well developed at $t = 439.02$ Myr. The figure exhibits turbulent and highly structured nature of the gas and the magnetic field in the bulge region. One can see turbulent poloidal field lines excited by MRI and Parker instability, whereas the toroidal component slightly dominates the poloidal (radial and vertical) component as will be discussed in \S 3.3. In the lower panel that zooms in the central region, we pick up $\sim$-shaped field lines excited by Parker instability, which are actually observed in the Galactic center region \cite{Fukui2006}.

Figure 3 shows the velocity field with the density, $n$, at the midplane ($\theta = \pi/2$) at different times. The left panel presents the result at the same time as in Figure 2 and the right panel shows the result at 2.6 Myr later than the left panel, where this time difference ($\approx 2.6$ Myr) roughly corresponds to $\approx 1/3$ of the rotation time at $R = 0.1$ kpc. These two panels show that radial motions are stochastically excited particularly around $R \approx 0.5$ kpc. Outward motions ($v_R > 0$) appear to dominate, whereas one can also recognize inflows ($v_R < 0$) in some regions. These behaviors are a result of the magnetic field as will be discussed in more detail later.

3.2 $l$–$v$ diagrams

Figure 4 shows Galactic longitude–velocity ($l$–$v$) diagrams observed from the LSR at different times that correspond to Figure 3. The solar system is assumed to rotate with $240$ km s$^{-1}$ in the clockwise direction at $R = 8$ kpc \cite{Honma2012} and $\phi = -\pi/2$, namely $(v_x, v_y, v_z) = (-240, 0, 0)$ km s$^{-1}$ at $(x, y, z) = (0, -8, 0)$ kpc in the Cartesian coordinates. The contours indicate the column density in units of $10^{21}$ cm$^{-2}$, integrated along the direction of line of sight. We use the grid points with high-density regions where $n > 100$ cm$^{-3}$, because the high-density regions more or less trace the cool molecular gas, although our simulation treats one-fluid gas and does not distinguish molecules, neutral atoms, or ions.

Parallelogram-like shapes are observed in the central region as a consequence of the excited radial motions shown in Figure 3. Comparing the two panels, the shape changes with time on account of the time-dependent nature of the radial flows. Moreover, one can see that the shape is not symmetric because the distribution of the excited radial flows is not axisymmetric or bisymmetric. Interestingly, the parallelogram shape obtained in the Milky way is not
Noncircular Motion and Outflows in the Galactic Bulge

Figure 3. Face-on views of density in units of \( n \, \text{cm}^{-3} \) (colour) and velocity field (arrows) at the midplane at different times, \( t = 439.02 \) Myr (left) and 441.61 Myr (right).

Figure 4. \( l-v \) diagrams at different times, \( t = 439.02 \) Myr (left) and 441.61 Myr (right). The grid points with high-density regions, \( n > 100 \, \text{cm}^{-3} \), in \(|z| < 0.2 \, \text{kpc}\) are used to derive the column density in units of \( 10^{21} \, \text{cm}^{-2} \) (colour) by integrating \( n \) along the direction of line of sight. In the horizontal axis, both Galactic longitude, \( l \) degree, (bottom axis) and the corresponding transverse distance, \( x \) kpc, at \( y = 0 \) kpc (top axis) are shown, where the solar system is located at \((x, y) = (0, -8) \) kpc.

We examine the time-dependency of the parallelogram-like feature in Figure 3. The solid lines in the top panel shows the time-evolution of the maximum and minimum velocities (\( v_{\text{max}} \) & \( v_{\text{min}} \)) for column density \( > 0.5 \times 10^{21} \, \text{cm}^{-2} \) at \( l = 0 \) degree; they correspond to the positions where the upper and lower sides of the parallelogram cross the vertical line of \( l = 0 \) degree in the \( l-v \) diagram. The figure shows that \( v_{\text{max}} \) and \( v_{\text{min}} \) vary within 50-150 km s\(^{-1}\) with time. Basically \( v_{\text{max}} \) and \( v_{\text{min}} \) change independently each other, and then, the shape of the symmetric parallelogram is not always kept but distorted with time as seen in Figure 4.

In Figure 4, the time evolution of the motion of the gas at \((x, y) = (0, \pm 0.5)\) kpc is also shown (dashed lines) for comparison. These lines indicate that the direction of the radial motion tends to be outward (\( v < 0 \)) for the front side and \( v > 0 \) for the back side), whereas inward motions are also seen occasionally.

The bottom panel presents the slope of the parallelogram measured near \( l = 0 \), which is derived from the average in the region with \(-0.72 < l < 0.72\) deg, corresponding to \( x \approx \pm 100 \) pc. The solid and dashed lines denote the top and bottom sides of the parallelogram, which mostly reflect far and near sides with respect to the Galactic center, respectively. The top and bottom sides change independently because of the non-axisymmetric excitation of radial flows. The slopes vary from 15 to 90 km s\(^{-1}\) deg\(^{-1}\), which covers the observed slope, \( \approx 20 \) km s\(^{-1}\) deg\(^{-1}\), for the top side of the parallelogram and \( \approx 55 \) km s\(^{-1}\) deg\(^{-1}\) for the bottom side (Tori et al. 2010a).
3.3 Origin of Noncircular Motion
–Roles of Magnetic Field–

Our MHD simulation shows that noncircular motions are excited, even though the axisymmetric gravitational potential is adopted. Here we discuss the roles of the magnetic field in driving the radial gas flows by inspecting the numerical data. In Figures 6 and 7 we present the radial profile of various quantities averaged over azimuthal ($\phi$) and vertical ($z$) directions and over time $t$. In these figure we focus on the inner region, $R \lesssim 2$ kpc, because MHD turbulence is still developing in the outer region. We take the average of a physical quantity, $A$, as follows:

$$\langle A \rangle = \frac{1}{2\pi} \int_{t_1}^{t_2} dt \int_{-\pi}^{\pi} d\phi \int_{z_1}^{z_2} dz A/[2\pi(t_2 - t_1)(z_2 - z_1)],$$

(12)

where we set $t_1 = 436.68$, $t_2 = 485.21$ Myr, $z_1 = -1$, and $z_2 = +1$ kpc. For the quantities concerning velocity, we adopt density-weighted averages; the average of flow velocity and root-mean squared (rms) velocity is taken by

$$\langle v \rangle = \frac{\langle pv \rangle}{\langle \rho \rangle},$$

(13)

and

$$\sqrt{\langle v^2 \rangle} = \sqrt{\frac{\langle pv^2 \rangle}{\langle \rho \rangle}},$$

(14)

while the simple average is taken for the quantities on magnetic field.

Figure 6 presents the plasma $\beta$ value,

$$\beta = \frac{\langle p \rangle}{\langle B^2 \rangle} = \frac{8\pi\langle p \rangle}{\langle B^2 \rangle},$$

(15)

which is the ratio of gas pressure to magnetic pressure (top panel), and the $\alpha$ value (bottom panel; solid line) (Shakura & Sunyaev 1973),

$$\alpha = \langle \alpha_R \rangle + \langle \alpha_M \rangle = \frac{\langle pv \delta v_\phi \rangle}{\langle p \rangle} - \frac{\langle B_R \delta B_\phi \rangle}{4\pi\langle p \rangle},$$

(16)
Figure 7. Radial distribution of various quantities. The data is averaged over the azimuthal direction in full rotation (2π), over the vertical direction within |z| < 1 kpc (except for panel (a)), and the time t = 436.68–485.21 Myr. (see text). (a): The strength of differential rotation, ∂ln Ω/∂ln R at the midplane (solid line); The average is not taken over the z component but over the φ component and time. The dashed line represents the initial condition. Rigid-body rotation (∂ln Ω/∂ln R = 0), flat rotation (= −1), and Keplerian rotation (= −3/2) are shown by dotted lines for reference. (b): R (solid), φ (dashed), and z (dotted) components of root-mean squared (rms) magnetic field in units of µG. The dotted line with a constant slope denotes the initial vertical magnetic field. (c): Root mean squared radial velocity, √<v_R^2> (solid), and mean radial velocity, <v_R> (dashed and dotted lines for positive and negative values).

which is the sum of Reynolds (α_R; dotted line) and Maxwell (α_M; dashed line) stresses. The fluctuation component, δv_φ, is derived by subtracting the mean rotation,

δv_φ = v_φ - <v_φ>.

(17)

The top panel of Figure 8 shows that the plasma β is below 100 in the bulge region, R < 1 kpc, which is much smaller than the initial value, β ≈ 10^3–10^4, as a consequence of the amplification of the initial weak magnetic field. The bottom panel shows that a large α value > 10^{-2} is obtained. In the inner bulge, R < 0.3 kpc, the Maxwell stress dominates the Reynolds stress. In the outer bulge, the Reynolds stress exceeds the Maxwell stress, and they both show bumpy structures, which reflects the complicated rotation profile as discussed from now.

Figure 8(a) presents the time and φ-averaged strength of the radial differential rotation, ∂ln Ω/∂ln R, at the midplane. Note that ∂ln Ω/∂ln R = 0, −1, −3/2 correspond to rigid-body, flat, and Keplerian rotations, respectively. The
The magnetic field strength is amplified not only by both MRI and field-line stretching.

Equations (18) and (19) show that stronger differential rotation amplifies magnetic field faster by both MRI and field-line stretching.

Figure 9. Additional mechanism that drives radial flows. The initial setting is the same as in Figure 8. Radial magnetic field, which is triggered by MRI in our simulation, is amplified to general toroidal field by the differential rotation selectively in the red region (Region 2). The magnetic pressure, \( p_B \), of the toroidal field is larger than \( p_B \) in the neighboring regions. Then, radial flows are generated by the magnetic pressure gradient force.

Magnetic field is effectively amplified on account of the strong gas pressure-gradient force (Equation 5) which is consistent with an observational lower limit, \( \sim 50 \mu G \) (Crocker et al. 2010) and an empirical estimate, \( \sim m G \), based on multiple observations (Ferrière 2009).

The effective amplification of the magnetic field around the location for the maximum differential rotation at \( R \approx 0.6 \) kpc gives a bump in the Maxwell stress, \( \alpha_M \) (Equation 16) as shown in dashed line in the bottom panel of Figure 6. \( \alpha_M \) determines the outward transport of angular momentum (e.g., Lynden-Bell & Pringle 1974) by magnetic field. The inhomogeneous distribution of \( \alpha_M \) indicates that spatially dependent gain or loss of the angular momentum takes place, which is illustrated by a simplified cartoon in Figure 8 in a region with the gain of angular momentum the rotation is accelerated, and vice versa. This leads directly to the increase or decrease of the centrifugal force, which excites radial motion. Although what is taking place in our simulation is more complicated, namely \( \alpha_M \) is distributed in a non-axisymmetric manner, and both outward and inward flows are generated even at the same \( R \) as exhibited in Figure 8, the simple conceptual cartoon in Figure 8 explains the essential point.

In addition to the inhomogeneous transport of angular momentum, magnetic pressure also contributes to the excitation of radial flows. In the outer bulge region near \( R \approx 1 \) kpc, the differential rotation is weak and the amplification of the magnetic field is suppressed there. Figure 8(b) exhibits the rapid decrease of the magnetic field strength with \( R \) in \( \approx 0.5 \) kpc. The rapid decrease of \( B_0^2 \) causes the radial pressure gradient, \(-\frac{1}{\rho} \frac{\partial \rho B_0^2}{\partial R}\), which drives outward radial flows (Figure 8).

We have discussed the two types of the processes, the inhomogeneous angular momentum transport and the magnetic pressure-gradient force, that generate radial flows. By inspecting each term in the momentum equation, (10), the former dominates the latter by \( \approx 2:1 \).

Figure 8(c) shows that the direction of the mean flow is outward (dashed line \( \langle v_R \rangle > 0 \)) in \( 0.3 < R < 0.5 \) kpc, which is expected from both processes. This radially outward flow also transports the angular momentum, which is a reason in part why the Reynolds stress (the bottom panel of Figure 6) shows a bump in \( 0.5 \approx R \approx 1 \) kpc. Compared to the mean flow, the rms velocity, \( \sqrt{\langle v_R^2 \rangle} \), at \( R \approx 0.5 \) kpc is quite large, \( \approx 40 \) km s\(^{-1}\), because the MRI triggered turbulence drives both inward and outward flows intermittently (Sano & Inutsuka 2001, see also movies of Figures 2 and 3), as discussed so far. This is the main reason why the simulated \( l-v \) diagrams show a thick parallelogram-like shape (Figure 4).

3.4 Non-axisymmetric Structure

As we have discussed in the previous subsection, the velocity field shows non-axisymmetric radial flows because of the intermittency of the MRI triggered turbulence. The density distribution also shows non-axisymmetric inhomogeneity, which is typical for the MRI turbulence as well (Suzuki & Inutsuka 2014), in the central region as exhibited in Figure 10. One can see multiple arm-like structure, and when measured at \( R \approx 50 \) pc, the density varies largely within, \( 1500 < n < 3800 \) cm\(^{-3}\), which roughly corresponds to \( 750 < n_{HI} < 1900 \) cm\(^{-3}\) in molecular number density.

It is well known that the Milky Way possesses the central molecular zone (CMZ), which contains molecular gas with mass \( \approx (5 - 10) \times 10^7 M_\odot \) within \( R < 200 \) pc (Morris & Serabyn 1996). The CMZ consists of non-axisymmetric
Recenty, the existence of outflows or winds in the Galactic center region are extensively discussed (Everett et al. 2008; Crocker et al. 2011), and it might be closely linked to the formation mechanisms of the Fermi bubbles via magnetic activity (Carretti et al. 2013). Our simulation cannot directly applicable to the Fermi bubbles since the simulation does not cover the region near the polar axis. However, the above rough estimate of the energetics of the outflow in our simulation shows that the magnetic field is a reliable mechanism in driving outflows from the bulge.

4 SUMMARY AND DISCUSSION

We have investigated the excitation of radial gas flows in the Galactic center region by the 3D global MHD simulation with the axisymmetric gravitational potential. The initial weak vertical magnetic field is amplified by the MRI at the beginning, and in addition eventually by the Parker instability and the field-line stretching owing to the differential rotation. In the bulge region, the final field strength is $\sim 0.5$ mG, and the plasma $\beta \sim 1 - 40$. Because of the gas pressure-gradient force, the equilibrium rotation frequency is non-monotonic with radial distance. The amplification of the magnetic field is systematically more effective in regions with stronger differential rotation. Then, the transport of the angular momentum is spatially dependent, and the acceleration or deceleration of the rotation speed occurs depending on regions. This breaks the radial pressure balance owing to the change of the centrifugal force, and excites radial flows of the gas in a time-dependent and non-axisymmetric manner. In addition, the radial component of the magnetic pressure gradient is produced, which also excites radial flows. As a result, the simulated $l-v$ diagram exhibits a time-dependent and asymmetric parallelogram shape. The rotation curve near the Galactic center exhibits complicated features (Sofue 2013). Our simulation implies that stochastically excited radial motion might be contaminate in these features.

© 2015 RAS, MNRAS 000, ??

Figure 10. Density structure in the Galactic center region at $t = 439.02$ Myr. (Zoomed-in view of the left panel of Figure 2.)

Figure 11. Vertical cut at $\phi = \pi/2$ of $1/\beta$ (colours) and velocity field (arrow) at $t = 439.02$ Myr.
In order to interpret the parallelogram in the CMZ, the elliptical orbit in the bar stellar potential has been used as the only viable model (Binney et al. 1991). The model may not be fully appropriate as the interpretation from an observational point. First, the bar potential alone is not able to create high-$b$ features up to 200 pc above the plane like the loops which are better explained as due to the Parker instability (Fukui et al. 2006). There is no known driving mechanism to expel gas up to that height by only stellar gravity. Second, the parallelogram is not symmetric in the $l$-$v$ diagram; the velocity gradient in the positive velocity, $\sim 20$ km s$^{-1}$ deg$^{-1}$, is significantly different by a factor of 3 from that in the negative velocity, $\sim 55$ km s$^{-1}$ deg$^{-1}$ (Torii et al. 2010a). The present model shows that the velocity gradient of the parallelogram is naturally produced as a time dependent manner, whereas it is not clear how such a difference is explained in the bar potential model.

On the other hand, we see some features are not reproduced in the present simulation. The large broad features like the clump 2 and the 5.5 deg feature are not reproduced in the present simulation. In our simulation we have assumed one-fluid gas and neglected heating and cooling with a simplified treatment of the locally isothermal gas. In order to treat dense molecular gas in a quantitative fashion, we should replace these simplifications. If radiative cooling, as well as adiabatic heating and cooling, is included, large density contrast between cool molecular gas and warm/hot gas will be naturally reproduced, which may explain the observed fine-scale features.

We have shown that the magnetic activity possibly produces the overall trend of the observed asymmetric parallelogram-shape in the $l$-$v$ diagram even though the axisymmetric gravitational potential is considered. It is also desirable to test quantitatively the importance of the magnetic activity in contrast to the role of the stellar bar potential in the noncircular motion of the gas after the cooling/heating effect is taken into account in our simulation.

Although in this paper we have focused on the bulge region of our Milky Way, results of our simulation can be applied to other galaxies. For example, Sakamoto et al. (2006) observed NGC 253 by the Submillimeter Array and reported that they found an expanding circumnuclear disk with $\sim 50$ km s$^{-1}$. The obtained position velocity diagrams show asymmetric parallelogram features in different wavelengths. These features are qualitatively similar to but quantitatively different from those obtained in the Milky Way. A possible explanation of the difference is the time variability inhering in the MHD turbulence, based on our simulation.

ACKNOWLEDGMENTS

This work was supported by Grants-in-Aid for Scientific Research from the MEXT of Japan, 24224005 (PI: YF). Numerical simulations in this work were carried out at the Cray XC30 (ATERUI) operated in CICA, National Astrophysical Observatory of Japan, and the Yukawa Institute Computer Facility, SR16000. TKS thanks Prof. Shu-ichiro Inutsuka and Dr. Kazunari Iwasaki for fruitful discussion.

REFERENCES

Baba J., Saitoh T. R., Wada K., 2010, PASJ, 62, 1413
Balbus S. A., Hawley J. F., 1991, ApJ, 376, 214
Balbus S. A., Hawley J. F., 1998, Reviews of Modern Physics, 70, 1
Bally J., Stark A. A., Wilson R. W., Henkel C., 1987, ApJS, 65, 13
Bania T. M., 1977, ApJ, 216, 381
Binney J., Gerhard O. E., Stark A. A., Bally J., Uchida K. I., 1991, MNRAS, 252, 210
Blitz L., Spergel D. N., 1991, ApJ, 379, 631
Bovy J. et al., 2012, ApJ, 759, 131
Carretti E. et al., 2013, Nature, 493, 66
Chandrasekhar S., 1961, Hydrodynamic and hydromagnetic stability. Oxford: Clarendon
Chuss D. T., Davidson J. A., Dotson J. L., Dowell C. D., Hildebrand R. H., Novak G., Vaillancourt J. E., 2003, ApJ, 599, 1116
Clarke D. A., 1996, ApJ, 457, 291
Crocker R. M., Jones D. I., Aharonian F., Law C. J., Melia F., Ott J., 2011, MNRAS, 411, L11
Crocker R. M., Jones D. I., Melia F., Ott J., Protheroe R. J., 2010, Nature, 463, 65
Dame T. M., Hartmann D., Thaddeus P., 2001, ApJ, 547, 792
de Vaucouleurs G., 1964, in IAU Symposium, Vol. 20, The Galaxy and the Magellanic Clouds, Kerr F. J., ed., p. 195
Enokiya R. et al., 2014, ApJ, 780, 72
Evans C. R., Hawley J. F., 1988, ApJ, 332, 659
Everett J. E., Zweibel E. G., Benjamin R. A., McCammon D., Rocks L., Gallagher, III J. S., 2008, ApJ, 674, 258
Ferrière K., 2009, A&A, 505, 1183
Fujishita M. et al., 2009, PASJ, 61, 1039
Fukui Y. et al., 2006, Science, 314, 106
Genzel R., Eisenhauer F., Gillessen S., 2010, Reviews of Modern Physics, 82, 3121
Hayakawa S., Matsumoto T., Murakami H., Uyama K., Thomas J. A., Yamagami T., 1981, A&AI, 100, 116
Honma M. et al., 2012, PASJ, 64, 136
Kato Y., Mineshige S., Shibata K., 2004, ApJ, 605, 307
Kent S. M., 1992, ApJ, 387, 181
Kim W.-T., Stone J. M., 2012, ApJ, 751, 124
Koda J., Wada K., 2002, A&A, 396, 867
Kruĳssen J. M. D., Dale J. E., Longmore S. N., 2015, MNRAS, 447, 1059
Kudo N. et al., 2011, PASJ, 63, 171
Liszt H. S., Burton W. B., 1978, ApJ, 226, 790
Lynden-Bell D., Pringle J. E., 1974, MNRAS, 168, 603
Machida M. et al., 2009, PASJ, 61, 411
Machida M., Nakamura K. E., Kudoh T., Akahori T., Sofue Y., Matsumoto R., 2013, ApJ, 764, 81
Matsumoto T., Hayakawa S., Koizumi H., Murakami H., Uyama K., Yamagami T., Thomas J. A., 1982, in American Institute of Physics Conference Series, Vol. 83, The Galactic Center, Rieger G. R., Blandford R. D., eds., pp. 48–52
McNally C. P., Pessah M. E., 2014, ArXiv e-prints
Miyamoto S., Nagai R., 1975, PASJ, 27, 533
Molinari S. et al., 2011, ApJ, 735, L33
Morris M., Davidson J. A., Werner M., Dotson J., Figer D. F., Hildebrand R., Novak G., Platt S. R., 1992, ApJ, 399,
