GAS DYNAMICS IN THE MILKY WAY: A LOW PATTERN SPEED MODEL

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ABSTRACT

We present gas flow models for the Milky Way based on high-resolution grid-based hydrodynamical simulations. The basic galactic potential we use is from an $N$-body model constrained by the density of red clump giants in the Galactic bulge. We augment this potential with a nuclear bulge, two pairs of spiral arms, and additional mass at the bar end to represent the long bar component. With this combined model we can reproduce many features in the observed $(l,v)$ diagram with a bar pattern speed of $33 \text{ km s}^{-1} \text{kpc}^{-1}$ and a spiral pattern speed of $23 \text{ km s}^{-1} \text{kpc}^{-1}$. The characteristic of barred spiral arms play some role for the gas flow into the bar region.

Hydrodynamic models of the gas flow in the Milky Way have been able to reproduce many of the distinctive features in the $(l,v)$ diagrams for HI and CO data (Burton & Liszt 1993; Dame et al. 2001), even though no model has been able to provide a good match to all the observed features (Englmaier & Gerhard 1999; Fux 1999; Rodriguez-Fernandez & Combes 2008; Baba et al. 2010; Sormani et al. 2015b). A variety of barred potentials were used, including potentials derived from COBE or star count data, or potentials characteristic of barred $N$-body models. Besides the bar, also the Galactic spiral arms play some role for the gas flow (Bissantz et al. 2003; Seo & Kim 2014), by regulating the inflow of gas into the bar region.

Apart from the gravitational potential, the pattern speed of the bar is the most important parameter for the gas flow, because for a given mass distribution it sets the resonance radii where the gas flow needs to accommodate the transition from one closed orbit family to another. A number of early investigations concluded a relatively high value for the pattern speed, $50-65 \text{ km s}^{-1} \text{kpc}^{-1}$ (Englmaier & Gerhard 1999; Fux 1999; Debattista et al. 2002; Bissantz et al. 2003), such that the corotation radius of the bar would be located in the range $R_{CR} = 3.5-5 \text{kpc}$, but others have argued for lower values (Weiner & Sellwood 1999; Rodriguez-Fernandez & Combes 2008; Shen 2014; Sormani et al. 2015b).

Recently, Wegg & Gerhard (2013) measured the three-dimensional density of red clump giants (RCGs) in the barred Galactic bulge. This density, together with the kinematics from the BRAVA survey (Kunder et al. 2012), has since been used as a constraint in constructing dynamical models of the barred bulge using the made-to-measure (M2M) method (Portail et al. 2015b). Surprisingly, these models required a rather low pattern speed for the bar, $25-30 \text{ km s}^{-1} \text{kpc}^{-1}$, so that $R_{CR} > 7 \text{kpc}$.

In these models the bulge represents the central buckled, box/peanut part of a longer bar similar to many $N$-body bars (Combes & Sanders 1981; Raha et al. 1991; Martinez-Valpuesta et al. 2006; Shen et al. 2010). Star count studies extending to larger longitudes have indeed found a thinner bar outside the Milky Way’s barred bulge (e.g., Hammersley et al. 2000; Benjamin et al. 2005; Cabrera-Lavers et al. 2008; Wegg et al. 2015) that ends near $l \approx 27^\circ$–$30^\circ$. If these two components are aligned and form a single structure at an angle to the Sun of $\geq 27^\circ$, as suggested by Martinez-Valpuesta & Gerhard (2011) and found with the detailed RCG maps of Wegg et al. (2015), then the “long bar” component ends at $>4.7 \text{kpc}$ from the Galactic center. Because the bar cannot exist beyond corotation (Contopoulos 1980), this limits the pattern speed to $\Omega_b \leq 47 \text{ km s}^{-1} \text{kpc}^{-1}$ for a flat rotation curve at $220 \text{ km s}^{-1}$, lower than found by the majority of previous gas dynamics studies, but still significantly larger than the best-fitting pattern speed in the barred bulge dynamical models from Portail et al. (2015b).

The purpose of the present paper is to inquire whether the observed $(l,v)$ diagram can be explained by a gas flow model in such a low-$\Omega_b$ model, if we use a potential based on these dynamical models as an input to study the gas flow in a realistic Milky Way context.

The paper is organized as follows: In Section 2, we describe our galaxy models, model parameters, and the numerical method. In Section 3, we present the best-fitting gas model, and we explore the parameter space in Section 4. In Section 5, we
discuss our assumptions and the implications for our model and summarize our results.

2. GALAXY MODELS AND NUMERICAL METHOD

2.1. Hydrodynamical Simulation

We study here how gas responds to an imposed nonaxisymmetric barred galaxy potential \( \Phi_{\text{gal}} \) using hydrodynamic simulations. The potential is described in Section 2.2. The bar is assumed to rotate rigidly about the Galactic center with a fixed pattern speed \( \Omega_b = \Omega_0 \hat{z} \). We solve the dynamical equations in the frame corotating with the bar in the \( z = 0 \) plane. The equations of ideal hydrodynamics in this rotating frame are

\[
\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\Sigma \mathbf{u}) = -\nabla \cdot \mathbf{u},
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{\nabla \Sigma}{\Sigma} - \nabla \Phi_{\text{gal}} + \Omega_0^2 \mathbf{R} - 2 \Omega_b \times \mathbf{u}.
\]

Here \( \Sigma \) and \( \mathbf{u} \) denote the gas surface density and velocity, respectively.

Equation (1) and (2) are solved by a modified version of the grid-based MHD code *Athena* (Gardiner & Stone 2005; Stone et al. 2008; Stone & Gardiner 2009). By adopting a higher-order Godunov scheme, *Athena* conserves mass and momentum of the fluid within machine precision. We integrate the equations on a uniform Cartesian grid with \( 2048 \times 2048 \) cells which corresponds to a square box with a length of \( L = 30 \) kpc. The grid spacing is therefore \( \Delta x = \Delta y = 14.6 \) pc, comparable to the size of giant molecular clouds (GMCs). These high-resolution runs are necessary to capture the instabilities and turbulence of gas (also see Sormani et al. 2015a). We take the van Leer algorithm with piecewise linear reconstruction, choose the first-order flux correction, adopt the exact Riemann nonlinear solver, and apply the outflow boundary conditions at the domain boundaries (i.e., at \( |x| = L/2 \) or \( |y| = L/2 \)) for our hydrodynamic models. We do not impose a point symmetry relative to the Galaxy Center, thus allowing odd- \( m \) modes to grow in our models.

The real interstellar medium (ISM) in the Milky Way is multiphase and turbulent. The gas temperatures may differ by as much as a few orders of magnitude from inner region to outer part of the galaxy (e.g., Field et al. 1969; McKee & Ostriker 1977, 2007). The thin-disk approximation for the Milky Way is appropriate as the gas layer is very thin (~100 pc) for most of the disk region, and the assumption that the large-scale \((l,v)\) features are influenced primarily by the underlying large-scale Galactic potential is also reasonable. The limitations of the simplified gas description are summarized in Li et al. (2015). In this paper we fix the effective isothermal sound speed \( c_s \) to be 10 km s\(^{-1}\), which is the same as in previous studies (e.g., Fux 1999; Rodriguez-Fernandez & Combes 2008), and set up an exponential gas disk with surface density:

\[
\Sigma_{\text{gas}}(R) = \Sigma_0 \exp(-R/R_{\text{gas}}).
\]

The coefficient \( \Sigma_0 \) and the scale length of the gas disk \( R_{\text{gas}} \) here are \( 130 M_\odot \, \text{pc}^{-2} \) and 3.5 kpc, respectively, which gives a total gas disk mass of \( 1.0 \times 10^9 M_\odot \).

2.2. Gravitational Potential

Our gravitational potential is constructed from the superposition of several components. The overall rotation curve is shown in Figure 1. We began from a barred \( N \)-body potential, but found that a nuclear bulge, two pairs of spiral arms, and an enhanced thin long bar were needed to produce reasonable gas flow models. These potential components are observationally constrained and added for physical reasons with preselected functional forms. Therefore, we cannot expect to obtain a perfect \((l,v)\) diagram that fits observations in all details. The influence of each of these components on the gas flow is described in Section 4.

2.2.1. N-body Potential

The basis of the galactic potential is the dynamical model M80 constructed by Portail et al. (2015b, hereafter P15). This model was obtained by fitting the 3D density of RCGs (Wegg & Gerhard 2013) to match the BRAVA kinematics (Kunder et al. 2012) with the M2M method (de Lorenzi et al. 2007, P15). We take the midplane potential from this 3D M2M N-body model so that the box/peanut shape of the bulge is taken into account. The bar angle to the line of sight is \((27 \pm 2)^\circ\), and the axis ratios of the bar are \((10:6.3:2.6)\).

Because the data cover the inner \( 10^5 \) of the Galaxy, we expect the potential to be accurate in this region. However, as the gas flow depends on the full large-scale potential, this model requires modification. Therefore, we include additional components in the next subsections.

2.2.2. Nuclear Component

The \( N \)-body model was constrained by off-plane data that do not extend to the Galactic center. In the central \( \lesssim 300 \) pc observations show the presence of an additional nuclear bulge component (Launhardt et al. 2002), which is not faithfully represented in the \( N \)-body model since it is too close to the Galactic plane and not extended enough along the line of sight to be resolved by the RCG star counts. We therefore add a potential calculated from the model density found by Launhardt et al. (2002):

\[
\Phi_{\text{nb}}(R) = -\frac{\gamma_0}{2} LG(1 + n R \Gamma(0.2, c) - q \Gamma(0.4, c))/R.
\]

According to Launhardt et al. (2002), the nuclear bulge is a superposition of two components, both of which follow the equation above. \( G = 4.302 \times 10^{-6} \text{kpc} M_\odot^{-1} \text{km}^2 \text{s}^{-2} \) is the gravitational constant, \( \Gamma \) is the incomplete gamma function, \( c = (p R)^{2} \), and \( L, n, p, q \) are coefficients. We use a mass-to-light ratio \( \gamma_0 \) of 2 suggested by Launhardt et al. (2002). For the first component, \( L = 8.09 \times 10^{8} L_\odot \), \( n = 3.48 \, \text{kpc}^{-1} \), \( p = 7.74 \, \text{kpc}^{-1} \), \( q = 0.45 \); for the second component these values are \( L = 4.88 \times 10^{8} L_\odot \), \( n = 1.90 \, \text{kpc}^{-1} \), \( p = 4.22 \, \text{kpc}^{-1} \), \( q = 0.45 \), respectively. The total mass of the nuclear bulge component is \( 1.4 \times 10^9 M_\odot \).

2.2.3. Spiral Arms

The gas under a spiral arm perturbation would show clear density contrast between the arm and interarm regions, which
produces features and voids in the \((l, v)\) diagram (Bissantz et al. 2003). Using over 100 trigonometric parallaxes of masers associated with young high-mass stars, Reid et al. (2014) mapped out the detailed shapes of the four major spiral arms in the Milky Way. For simplicity we include the four spiral arms with two separate, but identical in shape, pairs of logarithmic \(m = 2\) spiral arm potentials, offset by 20°.5 in azimuth. We parameterize the potential of each pair of the \(m = 2\) spiral arms with a form motivated by Junqueira et al. (2013):

\[
\Phi_{sp}(R, \varphi) = \begin{cases} 
-\zeta_{sp}R e^{-\frac{R}{\epsilon_{sp}}[1-(\cos(m\varphi-f_{m}(R))-R/\epsilon_{m})]} & R \geq R_{sp} \\
-\zeta_{sp}R e^{-\frac{R}{\epsilon_{sp}}[1-(\cos(m\varphi-f_{m}(R))-R/\epsilon_{m})]} \times e^{-(R-R_{sp})^2/2\sigma_{sp}^2} & R < R_{sp},
\end{cases}
\]

with the shape function as

\[
f_{m}(R) = \frac{m}{\tan(i)} \ln(R/R_{i}) + \gamma.
\]

Here \(m = 2\), representing two spiral arms, \(\zeta_{sp} = -800\) (km s\(^{-1}\))^2 is the perturbation amplitude, \(\epsilon_{sp} = 4\) kpc is the scale length of the spiral, \(i = 12.5\) is the pitch angle, \(\sigma = 2.35\) kpc is the half-width of the spiral arms in the azimuthal direction (the true width in a direction perpendicular to the arms is given by \(\sigma_{\perp} = \sigma \sin(i)\)), \(R_{i} = 8\) kpc, and \(\gamma = 139.5\) and 69.75 for these two pairs of arms are just the phase angles. Inside of \(R_{sp} = 9\) kpc, the spiral strength decays toward the center in a Gaussian form with a dispersion \(\sigma_{sp} = 1.5\) kpc. This is used for abating the effects of spiral arms inside the bar’s corotation radius (Kim & Ostriker 2006). The Local Arm forms self-consistently in our simulations. All the spiral arms in our best-fitting model match the shape of observed spiral arms (Reid et al. 2014) reasonably well (see Section 3).

In order to give a rough estimate of the mass of the spiral arms we used, we assume a vertical isothermal sheet potential profile for the spiral arm model in Equation (5):

\[
\Phi_{sp}(R, \varphi, z) = \Phi_{sp}(R, \varphi) \times \left( \frac{z_{0}}{1\text{kpc}} \ln[\cosh(z/z_{0})] - 1 \right) \times \left( \frac{z_{0}}{1\text{kpc}} \ln[\cosh(z/z_{0})] - 1 \right)
\]

which approximately corresponds to a 1D vertical density profile \(\rho_{sp}(z) \propto (1/kpc/z_{0})\text{sech}^{2}(z/z_{0})\) for \(z_{0} \ll R\). Then we use the 3D Poisson equation \(\nabla \cdot [\Phi_{sp}(R, \varphi, z)] = 4\pi G \rho_{sp}(R, \varphi, z)\) to derive the volume density and integrated mass. This does not exactly correspond to the analytic profile and may have some negative densities, which, however, have a small effect as long as \(z_{0}\) is less than 0.2 kpc. For our mass estimate we adopt \(z_{0} = 0.05\) kpc as suggested by Wegg et al. (2015). The resulting total mass of the spiral arms is then \(2.1 \times 10^{9} M_{\odot}\) within \(2z_{0}\) (0.1 kpc) and varies only slightly if we use \(z_{0} = 0.1\) kpc.

The pattern speed of the spiral arms should be lower than the bar pattern speed, so that the spirals could have a larger corotation radius, which is important for channeling a continuous gas flow inward (Section 4.2). In a recent work, Junqueira et al. (2015) used open clusters and the red giants from APOGEE to derive a robust estimate of the spiral pattern speed of \(23.0 \pm 0.5\) km s\(^{-1}\) kpc\(^{-1}\). We tested other spiral pattern speed values and find that the best values to give a reasonable gas flow are within the range of 21–24 km s\(^{-1}\) kpc\(^{-1}\). Therefore, we adopt \(\Omega_{sp} = 23.0\) km s\(^{-1}\) kpc\(^{-1}\). This value is consistent with previous simulations (e.g., Bissantz et al. 2003; Pettitt et al. 2014).

### 2.2.4. Long Bar and Leading Ends

The \(N\)-body model was based on star counts that were not constrained outside the bulge, so that the mass of the bar outside the bulge, or long bar, is underestimated. The existence of a thin long bar component in the Milky Way is indicated by a variety of near-IR and mid-IR star counts (Hammersley et al. 1994; Benjamin et al. 2005; Cabrera-Lavers et al. 2008; Wegg et al. 2015). Initially the data appeared to show that the in-plane long bar substantially misaligned with the Milky Way’s bulge bar. Martinez-Valpuesta & Gerhard (2011) offered a plausible explanation for a slight misalignment of the two components: the bulge bar could have developed leading ends through interaction with the adjacent spiral arm heads. A large misalignment was not supported by the new analysis of Wegg et al. (2015), which is based on a more homogeneous analysis of a wider range of data and limits a possible misalignment to a few degrees. The aligned bulge–long bar structure found by their work agrees with results from simulations and photometry of barred galaxies, while two misaligned bars with similar sizes are not observed in external galaxies. In any case, two independently rotating bars should align with each other through dynamical coupling in a few rotation periods, unless one bar is much larger than the other (Debattista & Shen 2007; Shen & Debattista 2009; Du et al. 2015), which is not the case in the Milky Way. We augment the mass in the \(N\)-body model long bar with a component described by the following equation:

\[
\Phi_{lb}(R, \varphi) = -\zeta_{lb}R e^{-\frac{R}{\epsilon_{lb}}[1-(\cos(m\varphi-f_{m}(R))-R/\epsilon_{m})]} \times e^{-(R-R_{lb})^2/2\sigma_{lb}^2} e^{-(\varphi-\varphi_{lb})^2/2\sigma_{lb}^2}.
\]

This is the spiral arm potential tapered by two Gaussian functions though \(R\) and \(\varphi\) direction. For our best model, we adopt \(m = 2\), \(R_{i} = 8\) kpc, \(\sigma = 139.5\), and \(i = 12.5\), which are the same as for the spiral arm part. The amplitude \(\zeta_{lb}\), the scale length \(\epsilon_{lb}\), and the half-width \(\sigma\) are \(-2000\) (km s\(^{-1}\))^2, 3.8 kpc, and 5.5 kpc, respectively. For the two Gaussian functions, we use \(R_{lb} = 5.0\) kpc, \(\varphi_{lb} = 2.5\), \(\sigma_{lb} = 0.8\) kpc, and \(\sigma_{lb} = 15\), giving a shape leading by \(2\sigma_{lb}\). Using the method described in Section 2.2.3, we estimate the mass of the additional long bar component to be \(8.2 \times 10^{9} M_{\odot}\) within \(2z_{0}\) (0.1 kpc), which is in good agreement with the value of \(7.3 \pm 8.8\) \(10^{9} M_{\odot}\) measured by Wegg et al. (2015).

### 3. BEST-FITTING MODEL FOR THE MILKY WAY

We show our best-fitting gas flow model for the Milky Way in Figure 2. This model contains the potential from P15, together with a nuclear bulge, two pairs of \(m = 2\) spiral arms, and a long bar component as described in the previous section. The pattern speed of the bar is \(33\) km s\(^{-1}\) kpc\(^{-1}\), and for the spiral arms it is \(23\) km s\(^{-1}\) kpc\(^{-1}\). The gas surface density map is shown in the left panel, and the corresponding \((l, v)\) diagram

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is shown in the right panel. To obtain the \((l, v)\) diagram, we assume that the Sun is located at \((x, y) = (0 \text{ kpc}, -8.3 \text{ kpc})\) (Chatzopoulos et al. 2015) with a velocity vector of \((-210 \text{ km s}^{-1}, 0 \text{ km s}^{-1})\). The bar angle to the Sun–Galactic center line is 27°, and the bin size in the \((l, v)\) diagrams is \(\Delta l = 0.5°\) and \(\Delta v = 3 \text{ km s}^{-1}\).

The use of the term “best-fitting” does not mean that we fit the model to the observational data, which is a challenging task (also see Sormani & Magorrian 2015). We use the criterion “approximately reproduces selected features” (i.e., the black lines and dots in the right panel of Figure 2). Gas flow models that can better reproduce more of the selected features are preferred, and the best-fitting model is the one that reproduces the most features.

From the surface density map, we see that the locations of the spiral arms agree reasonably well with those traced by the high-mass star-forming regions (HMSFRs) in Reid et al. (2014; white dashed lines). The minor offset between the model and the observations is due to our use of a uniform constant pitch angle (12°.5) for all of our four spiral arms, whereas the results of Reid et al. (2014) imply that the pitch angle for each arm varies from 6°.9 to 19°.8. Nevertheless, considering the thickness of the spirals and the measurement errors in the observations, the model with one common pitch angle seems reasonable to describe the locations of the observed spiral arms at \(R \gtrsim 7 \text{ kpc}\). Note that the Local Arm (and its counterpart at the opposite side of the Galaxy) here is self-consistently generated by the imposed spiral arm potentials, and it has a slightly smaller pitch angle compared to the four main spiral arms. For \(R \lesssim 7 \text{ kpc}\), the gas flow is mainly dominated by the bar, and the spiral arms in this region align themselves with the bar with a larger pitch angle. In the innermost region \((R \lesssim 4 \text{ kpc})\), we see a typical gas flow driven by the bar, with a pair of off-axis shocks (corresponding to the dust lanes) and a circumnuclear ring, which is commonly observed in nearby barred galaxies (e.g., Sanders & Huntley 1976; Athanassoula 1992; Buta & Combes 1996; Martini et al. 2003).

The right panel of Figure 2 shows the \((l, v)\) diagram of the model. The black lines and symbols depict the features identified by Rodriguez-Fernandez & Combes (2008) and the terminal velocity curves deduced from various observations, respectively. At negative \(l\), the tangent points around \(l = -50°\) and \(-70°\) are very well reproduced, but around \(l = -30°\) the terminal velocity of the model is \(~30 \text{ km s}^{-1}\) lower than the observations. At positive \(l\), the tangent point around \(l = 30°\) is offset in the model by about 5°, and the tangent point around \(l = 50°\) is not obvious as the Sagittarius arm here is weak. The model seems to produce more features on the \((l, v)\) diagram compared to the observed one, as the spiral arms in our model are continuous all the way from the Galactic center to the outer part, and we have two more weak spiral arms (the Local Arm and its counterpart at the other side) generated by the imposed spiral potential. The former leads to some features like the segment between \(l = -10°\) and \(l = -50°\), which should be a part of the Scutum arm, and the latter leads to some features like the segment at the right side of the Sagittarius arm, which should be a part of the Local Arm (see Figure 3 for a clearer view).

The Galactic bar mainly dominates for \(l \lesssim 30°\), as the bar ends at \(~27°\). In the \((l, v)\) diagram the Molecular Ring corresponds to the four strong arms at the bar end. The formation of these four arms may be due to the 4:1 resonances. The Near and Far 3 kpc arms are the arms that wrap up the bar; they are roughly reproduced in the \((l, v)\) diagram. The bump at \(l \sim 10°\) is \(~30 \text{ km s}^{-1}\) lower than the observations (some studies call this feature the 135 km s\(^{-1}\) arm; e.g., Fux 1999). In the very central region, the Connecting arm and Bania’s Clump 2 are \(~3°\) offset from the observations; these features are associated with the dust-lane shocks. The CMZ is associated with the nuclear ring, which is slightly offset compared to the observations. The peak of the \((l, v)\) diagram at \(l = 30°\) is also roughly reproduced, but at \(l = -3°\) the model peak is \(~40 \text{ km s}^{-1}\) larger than the observed one. The gas in our simulations is roughly symmetric about the origin, while the observed dust lanes and nuclear ring in our Galaxy are slightly lopsided (Bally et al. 1987; Molinari et al. 2011). The discrepancy between the model and the observations in the \((l, v)\) diagram may be due to the lack of lopsidedness in the model.

We also give a better view for the links between the real structures in the face-on image and the features in the \((l, v)\) diagram (Figure 3). We see that the spirals form continuous ridges in the \((l, v)\) diagram, and some of them overlap with each other. The Molecular Ring is mainly dominated by two of the bar-driven spiral arms around the bar end and by the Scutum arm. The other two bar-driven spiral arms around the bar end form the Near 3 kpc arm and the 135 km s\(^{-1}\) arm, and the Far 3 kpc arm is actually some feathers (or a weak spiral arm) between the Molecular Ring and the 135 km s\(^{-1}\) arm. The Connecting arm and the vertical features correspond to the two dust-lane shocks and the gas clumps on them. The face-on view of the gas flow here looks different from the reference model in Sormani et al. (2015b), although both of the models give a good representation of the \((l, v)\) diagram, suggesting some degeneracies in the \((l, v)\) space.

Despite minor differences between the model and the observations, the morphology and kinematics are in good agreement with the observations.
agreement with observations, which means that a low pattern speed model can also work for our Galaxy, although we need more components than a simple barred potential. We explain why we need the nuclear bulge, the spiral arms, and the long bar component in the next section.

4. MODEL VARIATIONS

4.1. The Effects of the Nuclear Bulge

We first demonstrate why a nuclear bulge is necessary in the center. Figure 4 illustrates the effect of adding the nuclear bulge. We see that there is an \( x_1 \)-type ring (which is elliptical and elongated along bar major axis; see the definitions in Kim et al. 2012) in the left panel by using the potential from P15 only. We know that the \( x_1 \)-type ring is rare in nature and there is no such a feature in our Galaxy. According to Li et al. (2015), decreasing bar pattern speed or increasing bulge central density could turn an \( x_1 \)-type ring into an \( x_2 \)-type ring (which is nearly circular and commonly observed). We also see in Figure 1 that in order to generate an inner Lindblad resonance (ILR) for the potential from P15, the pattern speed of the bar needs to be less than \( \sim 35 \text{ km s}^{-1}\text{kpc}^{-1} \). However, we have tried various bar pattern speeds even down to \( 10 \text{ km s}^{-1}\text{kpc}^{-1} \), and the \( x_1 \)-type ring still exists, which implies that changing bar pattern speed alone cannot generate an \( x_2 \)-type ring. This is probably due to the positive range of \( d(\Omega - \kappa/2)/dR \) at \( R < 1.2 \text{ kpc} \), which makes the gas form a pair of leading nuclear spirals at the beginning and then quickly turn into an \( x_1 \)-type ring (Combes 1996). The \( d(\Omega - \kappa/2)/dR \) at \( R < 1.5 \text{ kpc} \) can be modified to be negative simply by adding a dense center (Englmaier & Gerhard 1999; Li et al. 2015). Therefore, we
need more mass in the central region of P15 to generate a reasonable nuclear ring/disk.

Observations have shown evidence for a dense component in the very central part of the Milky Way. Launhardt et al. (2002) measured the COBE near-IR light at the Galactic center and found a nuclear bulge/disk of around 300 pc in radius and 45 pc in height. This component was not included in P15 because they were only able to go to ~1° from the plane before extinction and crowding became too high, while the nuclear bulge/disk becomes significant at ~50 pc or <0.5. By assuming a mass-to-light ratio of 2, the mass of the nuclear bulge is $1.4 \times 10^9 M_\odot$. We adopt their results, and the corresponding gas surface density is shown in the right panel of Figure 4. Now a typical bar-driven gas flow pattern appears, with a pair of dust lanes and an $x_2$-type nuclear ring. Note that adding such a nuclear bulge changes only the central region ($R \lesssim 1.5$ kpc) of the gas flow; the outer region is nearly the same for these two models.

The $x_2$-type nuclear ring corresponds to the parallelogram-shaped CMZ in the $(l, v)$ diagram, which has been studied for a long time. The size of the nuclear ring is an important parameter to constrain the shape of the potential as the gas in the ring follows $x_2$ orbits (Binney et al. 1991). In the observed $(l, v)$ diagram the CMZ spreads from $-1.5$ to $2^\circ$ (Bally et al. 1987), which is similar to the size of the nuclear ring in the smoothed particle hydrodynamics simulation done by Kim et al. (2011). Molinari et al. (2011) found that the cold gaseous nuclear ring (or disk) in the Galactic center has a radius of ~100 pc by using the far-infrared cameras on the Herschel satellite. Very recently, Schönrich et al. (2015) found a ~150 pc rotating nuclear disk composed of young stars using APOGEE data, which is probably formed from the gaseous nuclear ring. However, the nuclear ring in our simulation has a radius of ~300 pc. Considering the complicated environment in the Galactic center, it is possible that our assumptions for the gas might be oversimplified, and/or the nuclear bulge potential derived from the COBE image may not be accurate. Both would affect the radius of the nuclear ring. For example, a magnetic field of equipartition strength with the thermal energy of the gas could make the ring size smaller by a factor of ~2 (Kim & Stone 2012). Also, a lower mass-to-light ratio for the nuclear bulge would generate a smaller ring, but it is less sensitive to the bar pattern speed as long as the parameters of the nuclear bulge are fixed.

4.2. The Effects of the Spirals

In our best-fitting model we include two pairs of spiral arms with a pattern speed of 23 km s$^{-1}$ kpc$^{-1}$. Now we remove them from the potential to isolate their effects. The resulting gas surface density and $(l, v)$ diagram are shown in Figure 5. Without the imposed spiral arms, the bar drives the gas flow inward inside the corotation radius, as can be seen in the left panel of this figure, but the spiral arms driven by the bar in the outer regions are weak compared to our best model with an imposed spiral potential, and they have a flocculent structure around the bar corotation radius ($R_{CR} = 6.3$ kpc). Therefore, if we aim to reproduce the well-defined, continuous spiral arms suggested by the data of Reid et al. (2014; white dashed lines), we need to impose additionally a spiral arm potential (see also Bissantz et al. 2003).

One may argue that the self-gravity of gas may also help to form spirals without adding an external potential, but the resulting spirals may be transient and sensitive to the density of the initial gas disk. The more plausible scenario may be that the gas responds to the stellar potential as in our best-fitting model. This is supported by a recent study by Hou & Han (2015). They reported an obvious offset between the stellar spiral arms and the gas spiral arms in the Milky Way, which means the existence of a quasi-stationary density wave in our Galaxy, and the gas motion is mainly dictated by the distribution of stars. In the inner region of the left panel of Figure 5, the four strong arms at the bar end are driven by the N-body bulge bar and the thin long bar potential; therefore, they still exist and produce the Molecular Ring in the $(l, v)$ diagram. However, the Connecting arm, the Near and Far 3 kpc arm, and Bania's Clump 2 can barely be identified from the $(l, v)$ diagram. This is because the imposed spiral arm potential with a different
pattern speed channels gas flow inward from the outer regions of the Galaxy, making those features relatively long-lived and prominent. Without the imposed spiral potential, these features are obvious only at the beginning of the simulation but decay in a short time (Seo & Kim 2014), as the gas flows to the center along the shocks and accumulates in the central region, leading to the dissipation of the shock features with time. In the outer region of Figure 5, the arms driven by the bar are not obvious, and the tangent points at $|l| \gtrsim 30^\circ$ are poorly reproduced. This is due to the fact that the bar perturbation is weak outside the corotation radius, and the gas here still follows nearly circular orbits.

4.3. The Effects of the Long Bar

We remove the long bar component from our models to isolate the effects of this structure. The resulting gas surface density and $(l, v)$ diagram are shown in Figure 6. As this model includes the spiral arm potential, the tangent points, the Connecting arm, and Bania’s Clump 2 are better reproduced compared to the model in the last section. However, in this model the Molecular Ring seems to cover a larger region, and the bar-driven spiral arms at the bar end are quite weak. The reason why our model without the long bar component has so much less gaseous structure in the region around the end of the bar is because it does not have enough quadrupole potential there (also see Sormani et al. 2015b).

The additional mass added to the long bar in our best model generates four strong arms around the bar end, which have a larger pitch angle compared to the four large-scale spiral arms (Figures 2 and 5). Two of these four arms, connecting to the Scutum arm and the Perseus arm, result in a better description of the Near and Far 3 kpc arms than in the model without the additional mass. Therefore, we conclude that the long bar component is important for generating (Near and Far) 3 kpc arms that match the observations well.
The leading twist angle $\phi_{le} = 25.5$ we use in Equation (8) is not very important, i.e., if we set $\phi_{le} = 0^\circ$, the gas flow pattern is almost the same. The only difference is the existence of gas clumps (e.g., Bania’s Clump 2) on the dust lanes at a given epoch. In the simulation with $\phi_{le} = 0^\circ$, the gas clumps disappear at the moment when the spirals have finished a whole rotation relative to the bar (310 Myr), although they do appear at earlier times. This certain epoch is when the spiral arms arrive at the right position relative to the Sun, as in the bar corotation frame the spiral arms are rotating with respect to the bar. Since it is difficult to control the exact formation time of the transient gas clumps on the dust lanes, which tend to be stochastic, we still keep this very slight leading twist in our best-fitting model. These gas clumps mainly form the vertical features in the $(l, v)$ diagram as discussed in Section 5.

4.4. The Effects of Variations in the Rotation Curve

The exact rotation curve of the Milky Way is uncertain. In this section we show that this does not influence the results of this work. For example, the rotational velocity measured at the Sun radius is $V_{\odot,SR} = 238$ km s$^{-1}$ from Reid et al. (2014), which is $\sim20\%$ larger than the value of $210$ km s$^{-1}$ adopted in our best-fitting model. The difference between the circular velocity at the flat part in our model $V_{flat} \sim 210$ km s$^{-1}$ outside $\sim2$ kpc and in Reid et al. (2014) $V_{flat} \sim 238$ outside 5.5 kpc can be described by $\Delta V = V_{flat} - V_{flat} = 28 \times (R - 2)/(5.5 - 2)$, which results in terminal velocity differences between 0 and 28 km s$^{-1}$. But the solar velocity projected with the factor $\sin(l)$ also increases by 7–19 km s$^{-1}$ (2 kpc $\leq R \leq 5.5$ kpc corresponds to $14^\circ \leq l \leq 42^\circ$, which leads to $\sin(l) \times 28$ km s$^{-1} \sim 7$–19 km s$^{-1}$). So the resulting differences in the $(l, v)$ diagram between our best-fitting model and a model that uses the rotation curve of Reid et al. (2014) would be at an order of $O(10$ km s$^{-1}$), which is relatively small compared to the differences in the rotation curves.

We have also confirmed through simulations that the changes are small in the $(l, v)$ diagram by varying the rotation curve. We artificially add into our best-fitting model an extra radial force $F_{extra} = (V_{flat}^2 - V_{flat}^2)/R = (V_{flat}^2 - V_{flat}^2)(V_{flat}^2 - V_{flat}^2)/R$ as follows:

$$F_{extra}(R) = \begin{cases} 0 & R \leq 2 \text{kpc} \\ 28(R - 2)/(5.5 - 2) & 2 \text{kpc} < R \leq 5.5 \text{kpc} \\ +2V_{flat}/R & 2 \text{kpc} < R \leq 5.5 \text{kpc} \\ 28(28 + 2V_{flat})/R & 5.5 \text{kpc} < R. \\ \end{cases}$$

The corresponding rotation curve becomes flat at $R \sim 5.5$ kpc with a flat velocity of $V_{flat} = 238$ km s$^{-1}$. Note that $V_{\odot}$ of Reid et al. (2014) inside 5 kpc is nearly unconstrained. We run two experimental models with this potential: one has the same pattern speed of the bar (33 km s$^{-1}$ kpc$^{-1}$) and of the spiral arm (23 km s$^{-1}$ kpc$^{-1}$) with our best-fitting model, but now the corresponding corotation radius is 7.3 kpc for the bar and 10.4 kpc for the spiral arms; the other has a bar pattern speed of 37.7 km s$^{-1}$ kpc$^{-1}$ and a spiral pattern speed of 26.3 km s$^{-1}$ kpc$^{-1}$ to assure that the corresponding corotation radii for the bar and for the spiral arms are nearly the same as in our best-fitting model ($R_{CR-bar} = 6.4$ kpc and $R_{CR-spiral} = 9.1$ kpc). We find that the model with the same absolute pattern speeds instead of the same corotation radii is more similar to our best-fitting model with a relative difference about $O(10$ km s$^{-1}$). The reason that the pattern speed instead of corotation radius matters more is because the bar-related features are well inside $R \leq 4$ kpc ($l \leq 30^\circ$), and the effective potential here is relatively unchanged if the pattern speeds are fixed. Therefore, the same absolute pattern speeds in this case would give a similar $(l, v)$ diagram compared to our best-fitting model.

To achieve an even better-fitting gas flow pattern with the additional force above, the long bar needs to be more massive to get similar stream lines for a larger circular velocity. We then modify the long bar parameters $\sigma_l$ and $\epsilon_{lb}$ to be $25^\circ$ and $-1200$ km s$^{-1}$, respectively (the values in the best-fitting model are $15^\circ$ and $-2000$ km s$^{-1}$). The corresponding long bar pattern speed is $8.6 \times 10^9 M_\odot$, slightly higher than $8.2 \times 10^9 M_\odot$ in the best-fitting model. The resulting gas surface density and $(l, v)$ diagrams are plotted in Figure 7. The new model matches some structures in the $(l, v)$ diagram better (the Far 3 kpc arm, the Molecular Ring, and the CMZ) and others worse (the Near 3 kpc arm, the Connecting arm, and clumps) for the same pattern speed and is of similar overall quality. Our conclusion that low pattern speeds are possible is therefore maintained.

According to the experiments above, we believe that the differences in the rotation curve at $R > 2$ kpc cannot significantly change the conclusion of the bar pattern speed predicted in our paper. The mass distribution at $R \leq 2$ kpc is well constrained by the 3D density of red clump stars in Wegg & Gerhard (2013), so we do not vary it.

4.4.4. Different Bar Pattern Speeds

The pattern speed of the bar is an essential parameter to determine the dynamics of the galaxy, but its value in the Milky Way is still under debate. The gas kinematics is often used to constrain the bar pattern speed; thus, we vary this parameter in our best-fitting model to see whether other pattern speeds would also produce a reasonable $(l, v)$ diagram.

We run two additional models with bar pattern speeds of 23 and 43 km s$^{-1}$ kpc$^{-1}$ and plot their $(l, v)$ diagram together with our best-fitting model in Figure 8. We see that a lower or higher bar pattern speed does not reproduce most features in the $(l, v)$ diagram. For the bar pattern speed of 23 km s$^{-1}$ kpc$^{-1}$, which means a corotating bar and spiral arms, the Near 3 kpc arm moves to a lower part, and the tangent point at $l = -30^\circ$ becomes $-35^\circ$. The Molecular Ring seems to be less prominent, and the forbidden velocities at $(l > 0; v < 0)$ and $(l < 0; v > 0)$ are larger than the observed envelope. Similarly, the model with the bar pattern speed of 43 km s$^{-1}$ kpc$^{-1}$ gives a steeper 3 kpc arm, moving the tangent point at $l = -30^\circ$ inward to $-20^\circ$, and it makes the Molecular Ring extend to a larger region and the forbidden velocity move below the envelope. We also experimented with other bar pattern speeds within the range 23–43 km s$^{-1}$ kpc$^{-1}$. Of all the models we tested, the best-fitting model is still that with a pattern speed of 33 km s$^{-1}$ kpc$^{-1}$. While for our model parameterization the optimal range for the pattern speed is constrained within a few km s$^{-1}$ kpc$^{-1}$, the range may shift somewhat for different potentials in order to maintain the features in the $(l, v)$ diagram. Searching systematically through potential space is, however, challenging, due to the intractably
high number of free parameters (Sormani et al. 2015b). Our main result is therefore that pattern speeds as low as \(33 \text{ km s}^{-1} \text{kpc}^{-1}\) are consistent with the observed \((l, v)\) diagram.

### 5. DISCUSSION

Our models have shown that in order to generate a gas dynamics model that matches the Galactic \((l, v)\) diagram well, we need to include a nuclear bulge that helps to generate the nuclear ring, two pairs of spiral arms that continuously channel the gas flow inward to generate a prominent Connecting arm and clumps, and a strong long bar component that generates strong bar-driven arms at the bar end. All these components are motivated by observations, and we can understand how they affect the gas flow reasonably well.

The base potential of this simulation was taken from the M2M model of P15 for the Galactic box/peanut bulge. These authors found a low pattern speed for the bar (25–30 \text{ km s}^{-1} \text{kpc}^{-1}) by fitting the BRAVA stellar kinematic data in the bulge. Their value is consistent with the result obtained here (33 \text{ km s}^{-1} \text{kpc}^{-1}). Such a low value is consistent with the high pattern speeds (50–60 \text{ km s}^{-1} \text{kpc}^{-1}) obtained in previous gas dynamical studies (e.g., Fux 1999; Bissantz et al. 2003; Pettitt et al. 2014). These high pattern speed models have difficulties in explaining several features in the \((l, v)\) diagram (Sormani & Magorrian 2015), notably (1) the high-velocity peaks at \(l \approx \pm 3^\circ\); (2) the large forbidden velocities at \((l > 0; v < 0)\) and \((l < 0; v > 0)\); (3) the Near and Far 3 kpc arms; and (4) the vertical features, such as Bania’s Clump 2. We argue that our best-fitting model has improved in these four aspects:

1. The formation of high-velocity peaks is due to the large velocity jumps at the dust-lane shocks. A lower bar pattern speed or a more massive bar induces a stronger shock (Li et al. 2015), which gives higher-velocity peaks. These shocks may not have been sufficiently well resolved in some low-resolution simulations, as argued in Sormani et al. (2015a).

2. The forbidden velocity regions strongly depend on the bar pattern speed and depend weakly on the strength and length of the bar quadrupole, as well as on the bar angle, as suggested in Sormani et al. (2015b). Our best-fitting bar pattern speed of \(33 \text{ km s}^{-1} \text{kpc}^{-1}\) is consistent with their estimated range of \(30–40 \text{ km s}^{-1} \text{kpc}^{-1}\) based on forbidden velocity criteria.

3. The Near and Far 3 kpc arms are sensitive to the quadrupole, which is related to our long bar component. With enough quadrupole moment, the gas still favors a bar pattern speed around \(33 \text{ km s}^{-1} \text{kpc}^{-1}\) to give a good match to the 3 kpc arms. Sormani et al. (2015b) reached a similar conclusion on this point, but they offered a different explanation on the formation of the vertical features in the \((l, v)\) plane.

4. Sormani et al. (2015b) argue that the vertical features are different portions of the two dust-lane shocks, as the shocks show quite a spread in longitude when projecting to the \((l, v)\) plane (see their Figure 5 and our Figure 3). As the vertical features are quite strong and distinctive from the shocks in the \((l, v)\) plane, we think they are mainly turbulent gas clumps that fall to the CMZ along the dust-lane shocks. We observed in our simulation that some gas clumps fall into the CMZ region along the dust-lane shocks, likely due to the wiggle instability (Kim et al. 2014).

In summary, combining our results with those of authors who found bar pattern speeds in the range \(30–40 \text{ km s}^{-1} \text{kpc}^{-1}\) (Weiner & Sellwood 1999; Rodriguez-Fernandez & Combes 2008; Sormani et al. 2015b), we conclude that a gas flow model in a long, strong, and relatively slowly rotating bar potential gives a better description of the \((l, v)\) diagram than in high pattern speed models.

Dehnen (2000) and Antoja et al. (2014) suggested a bar pattern speed of \(53 \pm 3 \text{ km s}^{-1} \text{kpc}^{-1}\) based on the bimodality of the velocity distributions in the solar neighborhood. These authors explained this phenomenon in terms of the orbit shapes near the outer Lindblad resonance (OLR), where our Sun should be located slightly outside the OLR. However, in our best-fitting model the OLR lies far outside the Sun; instead, the outer 4:1 resonance is located at \(~8 \text{ kpc}\) (Figure 1). Whether this could generate similar structures in velocity space remains to be investigated. In addition, Minchev et al. (2009) and Antoja et al. (2009) argued that the influence of the spiral arms...
on the kinematic structures in the solar vicinity may be as important as that of the Galactic bar.

We note that the short extent of the peanut-shape bulge does not necessarily imply a fast-rotating bar, because the peanut shape is not necessarily caused by the vertical inner Lindblad resonance (vILR) as suggested by Pfenniger & Friedli (1991). In the models of Portail et al. (2015a), a strong peanut is maintained by families of three-dimensional brezel orbits, while the vILR is present only at radii outside the bulge. The hydrodynamical gas flow models provide an independent measurement of the bar pattern speed, and the value favored here agrees with the M2M models of P15.

Green et al. (2011) used the distribution of 6.7 GHz methanol masers to support the presence of a thin long bar with a 45° orientation from the Sun–Galactic center line. However, we show in Figure 9 that their data are also roughly consistent with our best-fitting model. The tilted blue ellipse (the 3 kpc arms traced by the masers) that is misaligned with the bulge bar (horizontal) was thought to be formed by a long bar with a different angle. We see in Figure 9 that our model can also produce a pair of similar misaligned 3 kpc arms.

A clear improvement to the current work is to use a more accurate potential, as the parameter space in our best-fitting model is still very large. But such a detailed search for a better model is challenging. The large-scale properties of the bar, the spiral arms, the long bar part, and the nuclear component, together with the shape of the rotation curve at all radii, need to be constrained and improved by further studies. Our assumptions for the gas flow appear reasonable on large scales, but they may be oversimplified in the CMZ region close to the center. Including more physics in the model might be helpful to explain the asymmetric and tilt properties of the CMZ, although this would also increase the parameter space considerably.

In summary, we propose a low bar pattern speed gas dynamics model for the Milky Way. We include the nuclear bulge, the spiral arms, and the long bar component to our potential, and they are all important to generate related (l, v) features. Our best model can better match the features in the (l, v) diagram than previous high bar pattern speed gas models, and we are still working to improve the model.
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