On the Interpretation of the $l$–$v$ Features in the Milky Way Galaxy

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Abstract

We modeled the gas dynamics of barred galaxies using a three-dimensional, high-resolution, $N$-body + hydrodynamical simulation, and applied it to the Milky Way in an attempt to reproduce both the large-scale structure and the clumpy morphology observed in galactic H I and CO $l$–$v$ diagrams. Owing to including of the multi-phase interstellar medium, self-gravity, star-formation, and supernovae feedback, the clumpy morphology, as well as the large-scale features, in observed $l$–$v$ diagrams were naturally reproduced. We identified in our $l$–$v$ diagrams with a number of not only large-scale peculiar features, such as the ‘3-kpc arm’, ‘135-km s$^{-1}$ arm’, and ‘Connecting arm’, but also clumpy features, such as ‘Bania clumps’, and then linked these features in a face-on view of our model. We give suggestions on the real structure of the Milky Way and on the fate of gas clumps in the central region.

Keywords: Galaxy: disk — Galaxy: kinematics and dynamics — galaxies: ISM — galaxies: spiral — method: numerical

1. Introduction

In order to understand the structure and dynamics of the Milky Way galaxy, the line-of-sight velocity of the interstellar medium (ISM) (e.g., H I, CO) is often used. This is used to determine the radial mass distribution (Soifue & Rubin 2001) and the spatial distribution (Oort et al. 1958; Nakanishi & Sofue 2003, 2006). These studies had to adopt a fundamental assumption: that the ISM rotates axisymmetrically in a purely circular fashion on the galactic plane. However, longitude–velocity ($l$–$v$) assumptions: that the ISM rotates axisymmetrically in a purely circular fashion on the galactic plane. However, longitude–velocity ($l$–$v$) diagrams of H I (Hartmann & Burton 1997) and CO (Dame et al. 2001) in the inner Milky Way galaxy are inconsistent with the circular motions. Moreover, the central stellar bar and spiral arms result in a non-axisymmetric gravitational potential. Thereby, there is much difficulty in reconstructing the true mass distribution (Koda & Wada 2002) and spatial distribution of the ISM from the line-of-sight velocities (Gómez 2006; Pohl et al. 2008; Baba et al. 2009 hereafter Paper I).

The peculiar features of the $l$–$v$ diagrams of H I and CO in the Milky Way galaxy are widely accepted to be non-circular flows under the influence of the stellar bar and spiral arms (see chapter 9 in Binney & Merrifield 1998). Binney et al. (1991) modeled ISM motion in terms of closed stellar orbits ($x_1$ and $x_2$ orbits), and interpreted the peculiar features seen in $l$–$v$ diagrams of the galactic central region ($|l| < 10^5$) as non-circular motions due to the galactic bar. Jenkins and Binney (1994) tried to reproduce the $l$–$v$ diagram of the central molecular zone (CMZ) by numerical simulations using the so-called sticky-particle method. Many hydrodynamical simulations of the ISM have also been performed in order to investigate the origin of the H I and CO $l$–$v$ diagrams of the galactic disk (Wada et al. 1994; Englmaier & Gerhard 1999; Weiner & Sellwood 1999; Fux 1999; Bissantz et al. 2003; Rodriguez-Fernandez & Combes 2008). These previous numerical studies showed that the large-scale features of the $l$–$v$ diagrams depend largely on the mass model of the bulge, stellar bar, and spiral arms along with the pattern speed and the location of the observer.

Englmaier and Gerhard (1999) performed hydrodynamic simulations of gas flows in the gravitational potential of the near-infrared luminosity distribution of the Milky Way (Binney et al. 1997). Their best-fit models qualitatively reproduced the number of observed features in the $l$–$v$ diagrams. Bissantz et al. (2003) extended the model of Englmaier and Gerhard (1999) to include stellar spiral arms, and showed that gas flows in models with stellar spiral arms match the observed $l$–$v$ diagram better than models without stellar spiral arms. Fux (1999) performed three-dimensional $N$-body + hydrodynamical simulations of the Milky Way, and gave a coherent interpretation of the main features standing out from the observed $l$–$v$ diagrams within the galactic bar. In particular, he showed that the trajectories of the gas associated with the Milky Way’s dust lanes can be reliably identified and the 3 kpc-arm appears as a gaseous stream rather than a density wave (Fux 2001). He also argued that the density center of the stellar bar wanders around the center of mass and that the resulting gas flow is asymmetric and non-stationary.

Advanced modeling of the galactic-disk provides further areas for comparisons between the theoretical models and observations; in addition, it can help us to understand the true
structure and dynamics of the galactic disk. However, these previous numerical studies adopted a rather simple modeling of the ISM and the stellar disk. First, an isothermal equation of state (EOS) with a velocity dispersion of \( \sim 10 \text{ km s}^{-1} \) (Wada et al. 1994; Englmaier & Gerhard 1999; Fux 1999; Weiner & Sellwood 1999; Bissantz et al. 2003), or a phenomenological model of the ISM (Rodriguez-Fernandez & Combes 2008) were used. The isothermal EOS would be a relevant approximation to investigate the global gas dynamics in galaxies; however, the ISM is obviously not isothermal. It is important to include an energy equation with appropriate cooling and heating terms in order to compare the numerical results with the H I and CO observations (e.g., Wada et al. 2000). The inhomogeneous nature of the ISM should be taken into account to investigate the gas dynamics on a local scale, or in the central regions of galaxies (Wada & Koda 2001). In fact, the observed \( l-v \) diagrams (e.g., Dame et al. 2001) show many ‘clumpy’ sub-structures, which were not seen in the previous computational \( l-v \) diagrams.

Secondly, self-gravitational interactions of the ISM were often ignored (Englmaier & Gerhard 1999; Weiner & Sellwood 1999; Bissantz et al. 2003). The self-gravity of gas can play a significant role in high-density regions, such as a central gaseous ring (Wada & Habe 1992; Wada et al. 1994; Fukuda et al. 2000). Furthermore, the self-gravity in gas along with the thermal instabilities causes complicated, non-circular motions in the multi-phase ISM (Wada et al. 2002). A bar was modelled with a fixed potential undergoing a rigid rotation, and stellar spiral arms were not considered (Wada et al. 1994; Englmaier & Gerhard 1999; Weiner & Sellwood 1999). In addition to the stellar bar, stellar spiral arms also result in non-circular motions of the gas (e.g., Fujimoto 1968; Roberts 1969; Shu et al. 1973). Bissantz et al. (2003) included stellar spiral arms, but the spiral arms were assumed to be rigid patterns.

In order to understand the origin of both large-scale structures and clumpy features in the observed \( l-v \) diagrams, we present a self-consistent high-resolution simulation of a disk galaxy, which consists of a stellar disk and the multi-phase ISM in a static dark-matter halo. Star formation from cold, dense gas and energy feedback from type II supernovae (SNe), which have not been included in previous models, are taken into account. We have simulated a model galaxy with a smaller mass than the Milky Way galaxy where the circular velocity at 8 kpc is 25% less than that in the Milky Way galaxy. This enables us to ensure a high mass resolution for the ISM. Despite this difference, the \( l-v \) diagram from our simulations can surprisingly reproduce many features noted in observations, suggesting that our method has potential to qualitatively reproduce features in the Milky Way galaxy with a more massive model. We are now preparing to run this ‘Milky Way model’ using ten-times the number of particles (i.e., \( > 10^7 \) particles) used in the work presented here.

In section 2, we describe our methodology, and in section 3 we report the numerical results. We present a qualitative comparison for these structures of the Milky Way galaxy via \( l-v \) diagrams in section 4. In section 5 we give a brief summary.

2. Numerical Method and Model Setup

We used the \( N \)-body/hydrodynamic simulation code ASURA (Saitoh et al. 2008, 2009) to solve the Newtonian equation of motions and the equations of hydrodynamics using the standard smoothed particle hydrodynamics (SPH) methods (Lucy 1977; Gingold & Monaghan 1977; Monaghan 1983):

\[
\rho_i = \sum_j m_j W(|x_i - x_j|, h),
\]

\[
\frac{d v_i}{d t} = -\sum_j m_j \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \nabla_i W(|x_i - x_j|, h) + g_i
\]

\[
- \nabla \Phi_{\text{DM}}(x_i),
\]

\[
\frac{d u_i}{d t} = \sum_j m_j \left( \frac{p_i}{\rho_i^2} + \frac{1}{2} \Pi_{ij} \right) (v_i - v_j) \cdot \nabla_i W(|x_i - x_j|, h)
\]

\[
+ \frac{\Pi_{ij}}{\rho_i},
\]

where \( \rho, p, u, v, x \), and \( \Phi_{\text{DM}} \) are the mass, density, pressure, specific internal energy, velocity, position of the gas, and the gravitational potential of the dark-matter halo, respectively. We assume an ideal gas EOS \( p = (\gamma - 1)\rho u \), with \( \gamma = 5/3 \). \( W(x, h) \) and \( h \) are the SPH smoothing kernel and the smoothing length, respectively, and \( h \) is allowed to vary both in space and time with the constraint that the typical number of neighbours for each particle is \( N_{\text{nb}} = 32 \pm 2 \). The artificial viscosity term \( \Pi_{ij} \) (Monaghan 1997) and the correction term to avoid large entropy generation in pure shear flows (Balsara 1995) are used. Radiative cooling of the gas, \( \Lambda \), was solved by assuming an optically thin cooling function with solar metallicity, which covered a wide range of temperature, 20 K through 10\(^{4} \) K (Wada & Norman 2001). Heating due to far-ultraviolet radiation (FUV) and energy feedback from SNe, \( \gamma = \Gamma_{\text{FUV}} + \Gamma_{\text{SN}} \), was also included. We assumed a uniform FUV field with matches that observed in the solar neighborhood,

\[
\Gamma_{\text{FUV}} = 10^{-24} \epsilon G_0 n_H \text{ [erg s}^{-1} \text{ cm}^{-3}] \]

(Wolfire et al. 1995), where \( \epsilon \) and \( G_0 \) are the heating efficiency (\( \epsilon = 0.05 \)) and incident FUV normalized to the solar neighborhood value (\( G_0 = 1 \)), respectively. The self-gravity of stars and SPH particles, \( g \), was calculated by the Tree with GRAPE method (Makino 1991). We here used a software emulator of GRAPE, Phantom-GRAPE (K. Nitadori et al. in preparation).

The models for the star formation and the SN feedback were the same as those in Paper I and Saitoh et al. (2008). We adopted a single stellar population approximation, with the Salpeter initial mass function (Salpeter 1955) and the mass range of 0.1–100 \( M_\odot \). If an SPH particle satisfies the criteria (1) \( n_H > 100 \text{ cm}^{-3} \), (2) \( T < 100 \text{ K} \), and (3) \( \nabla \cdot \mathbf{v} < 0 \), the SPH particle creates star particles following the Schmidt law (Schmidt 1959), with a local star-formation efficiency, \( C_s = 0.033 \), in a probabilistic manner (Tasker & Bryan 2006; Saitoh et al. 2008, 2009; Tasker & Bryan 2008; Robertson & Kravtsov 2008). The local star-formation efficiency, \( C_s \), is an unknown parameter. Saitoh et al. (2008), however, showed that the global (galactic) star-formation rate is not directly
proportional to the local star-formation efficiency, $C_s$, but mainly controlled by the gas mass in the high-density regions, which is statistically related to the global evolution of the ISM (for details, see subsection 5.2 in Saitoh et al. 2008). We treated Type II SNe feedback as injecting the thermal energy from SNe to the neighbour SPH particles. We assumed that stars with $>8 M_\odot$ experience Type II SNe and each SN releases an energy with a canonical value of $10^{51}$ erg. It was suggested that if the feedback energies are lower than the canonical value, it is hard to reproduce hot, diffuse halos around disk galaxies (Tasker & Bryan 2006, 2008).

We followed the same method presented in Paper I: we first embedded a pure $N$-body stellar disk with an exponential profile within a static dark-matter (DM) halo potential, whose density profile follows the Navarro–Frenk–White profile (Navarro et al. 1997). Using Hernquist’s method (Hernquist 1993), we generated the initial conditions for the stellar disk, which was then allowed to evolve for 2 Gyr, resulting in the formation of a stellar bar and multi-arms. At this point, we added a gaseous component to the stellar disk. This combined dark-matter potential embedded stellar disk + gas disk was used as the initial condition for the simulation presented in this paper. The model parameters of the dark matter halo, stellar disk, and gas disk are summarized in Table 1. The circular velocity curve is shown in figure 3a.

The total numbers of stars and gas particles are $3 \times 10^5$ and $10^6$, respectively, and the particle masses are $11000 M_\odot$ and $3200 M_\odot$. This gas particle mass allowed us to resolve the gravitational fragmentation of dense clumps of gas down to $\sim 10^5 M_\odot$ (Saitoh et al. 2008). In addition, a gravitational softening length of 10 pc in association with a typical smoothing length in dense regions of a few tens of pc means that structures larger than a few tens of pc are well resolved.

### Table 1. Model parameters for each mass component (dark halo, stellar disk, and gas disk).

| Component       | Parameter | Value       |
|-----------------|-----------|-------------|
| Dark halo       | Mass      | $6.3 \times 10^{11} M_\odot$ |
|                 | Radius    | $122$ kpc   |
|                 | Concentration | $5.0$ |
| Initial stellar disk | Mass     | $3.2 \times 10^{10} M_\odot$ |
|                 | Scale length | $3.0$ kpc |
|                 | Scale height | $0.3$ kpc |
| Initial gas disk | Mass      | $3.2 \times 10^9 M_\odot$ |
|                 | Scale length | $6.0$ kpc |
|                 | Scale height | $0.2$ kpc |

3. Results

#### 3.1. Three-Dimensional Structures

In figure 1a, we present a face-on view of the stars at $t = 1.24$ Gyr where $t = 0$ is the time when the gas component is added to the pre-evolved stellar disk. By this time, we can see a stellar bar with a semi-major axis of $\sim 3$–$4$ kpc. In $R = 5$–$10$ kpc, two-armed stellar spiral dominates, and outside $\sim 10$ kpc multi-armed spirals appear (see also figures 2 and 4 in Paper I). The Fourier amplitude of the dominant mode is $\sim 0.1$–$0.2$, which is consistent with the observational values of external disk galaxies (Rix & Zaritsky 1995; Zibetti et al. 2009).

Figure 1b present a face-on view of the cold gas ($T < 100$ K) overlaid on the stellar disk. Along the bar, a typical offset ridge structure of cold gas (dust lane) is formed and enhanced by the bar potential. There are many gas arms in the disk, but in contrast to previous isothermal simulations (e.g., Fux 1999) these arms are not smooth. There are also many substructures, such as clumps and filaments, in the inter-arm regions. Hence, it is not easy to trace any “single arm” from the central region to the outer disk, even for major spiral arms (see also figure 7c). The typical length and width of the gas filaments are $< 500$ pc and $\sim 100$ pc, respectively. These local structures, i.e., gas clumps and filaments, originate from their self-gravity, whereas large-scale structures, i.e., gaseous spiral arms, are driven by the stellar bar and spiral arms.

Figure 1c shows the surface density of the stars on the $(l, b)$-plane. The observer is assumed to be at $(R_0, \phi_0) = (8$ kpc, $25^\circ)$, where $R_0$ and $\phi_0$ are the galacto-centric distance and the position angle relative to the major axis of the bar, respectively (positive sign means for the anti-galactic rotation). Since many previous studies suggest that the orientation of the major axis of the galactic bar relative to us typically ranges from $15^\circ$ to $35^\circ$ (e.g., Binney et al. 1997; Fux 1999; Englmaier & Gerhard 1999; Bissantz et al. 2003; for a review, Merrifield 2004), we adopted a fiducial value of $\phi_0 = 25^\circ$. Due to our choice of $\phi_0 = 25^\circ$, we observed an asymmetry in the disk and bulge densities in longitude. This asymmetry agrees with near-infrared observational studies by COBE/DIRBE (Weiland et al. 1994; Dwek et al. 1995; Binney et al. 1997).

Surface density contours of the stellar disk are shown in figure 2. The principal axis of the surface density distribution for a given annulus of width $\Delta R = 0.5$ kpc are indicated by thick lines. Within a radius of $R < 4$ kpc, they well align in the same axis; however, the outer annuli show a different distribution axis. Figure 3b shows the pattern speeds of the principal axis. The pattern speeds for $R < 4$ kpc are more or less the same at $\sim 27$ km s$^{-1}$ kpc$^{-1}$, however, further out the pattern speed declines. Therefore, we determined that the semi-major axis of the stellar bar ($R_{\text{CR}}$) is $\sim 4$ kpc with a face-on axis ratio of $\sim 0.5$, and that the bar rotates as a rigid-body with $\Omega_{\text{CR}} \sim 27$ km s$^{-1}$ kpc$^{-1}$. Comparing $\Omega_{\text{CR}}$ and the angular frequency of the galaxy ($\Omega$), we infer the location of the co-rotation radius ($R_{\text{CR}}$) to be around $R = 5$ kpc, whose value is larger than $R_0$. This is consistent with theoretical studies (e.g., Contopoulous 1980) where a self-consistent bar is required to have $R_{\text{CR}}/R_0 > 1$, as well as observations of other barred galaxies (e.g., Aguerri et al. 2003). The inner and outer Lindblad resonances are located around $R = 1$ kpc and $10$ kpc, respectively. We note that the values of these bar parameters do not significantly change during the simulation ($t = 2$ Gyr). The inner Lindblad resonance (ILR) locates at $\sim 1$ kpc in this model, which is quite different from some previous models (e.g., Binney et al. 1991; Bissantz et al. 2003) that place the ILR at $\sim 100$ pc. This difference may be caused by differences of the mass model in the central region between our model and the Milky Way (see section 4).
3.2. The $l$–$v$ Features

Figure 4 shows a synthetic $l$–$v$ diagram derived from the cold gas distribution given in figure 1a. The diagram shows not only the peculiar features, but also the terminal velocity tangent points observed in the H I and CO $l$–$v$ diagrams. Furthermore, our synthetic $l$–$v$ diagram shows a clumpy morphology whose features possess a large velocity width (typically $\sim 10$–$20$ km s$^{-1}$), in agreement with CO $l$–$v$ diagrams (Dame et al. 2001). These clumpy features have not been reproduced in previous studies (Wada et al. 1994; Englmaier & Gerhard 1999; Bissantz et al. 2003; Fux 1999; Rodríguez-Fernandez & Combes 2008). We also show the $l$–$v$ diagram from a simulation with an isothermal EOS\textsuperscript{2} in figure 5a. Here, this model includes the self-gravity of the ISM. Unlike the $l$–$v$

\textsuperscript{2} We replaced the gas in the multi-phase run into the isothermal gas with $T = 10^4$ K at $t = 1.0$ Gyr, and then let it evolve for 240 Myr. Thus the stars distribute almost same as in the multi-phase run.

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high-velocity components in the regions of $l < 0$, $v > 0$ or $l > 0$, $v < 0$. The $l$–$v$ diagram at $t = 1.34$ Gyr, which is 100 Myr after the snapshot used for producing figure 4, is shown in figure 5d. One can notice that the non-axisymmetric features change on this time-scale. This reflects the fact that the stellar and gaseous spiral arms are not stationary, but time-dependent phenomena.

4. A Comparison to Real Structures in the Milky Way

4.1. Large-Scale Structures

A qualitative comparison between the numerical results and observations of the Milky Way is given in figure 6. We identify and trace schematically (solid lines), such as peculiar features as the Perseus (A), Outer (B), Connecting (C), 135-km s$^{-1}$ (D), 3-kpc (E), and Carina (F) arms. The terminal velocity tangent points, such as the Sagittarius (a), Scutum (b), Norma (c), and Centaurus (d) tangent points, are also shown schematically by boxes. Although the Perseus arm, Sagittarius tangent point, and central molecular zone (CMZ) are unclear in our model, other structures are clearly evident.

In order to see which features in the $l$–$v$ diagram correspond to structures in real space, we marked several major features with the same color in the face-on map (figure 7a, 7b). This comparison gives us insight to infer the real morphology of spiral arms in the Milky Way. For example, a prominent feature known as the “molecular ring” observed in CO $l$–$v$ diagrams does not necessarily correspond to a “ring” in real space, but might be a part of a nearby spiral arm (such as the one colored by light blue). Nakanishi and Sofue (2006) suggested that the molecular ring results from a combination of the inner part of the Sagittarius–Carina arm and the Scutum–Crux arm. The “3-kpc arm” (E) corresponds to an inner spiral arm (the one colored by green). It has been proposed that this arm arises from a lateral arm surrounding the bar (figure 16 in Fux 1999), or a small arm starting from the bar-end (figures 13 and
Fig. 4. Synthetic $l$–$v$ diagram in the range $|b| < 1\degree$ derived from the cold gas ($T < 100$ K) distribution given in figure 1a ($t = 1.24$ Gyr). The observer is located at the mark point indicated in figure 1, and has pure circular motion. The contribution of each SPH particle to the synthetic $l$–$v$ diagrams is weighted by its inverse squared distance relative to the observer in order to mimic the flux decline of point source. The gases with $d < 500$ pc are not displayed.

Fig. 5. Same as figure 4, but for (a) the isothermal gas with $T = 10^4$ K, (b) $\phi_b = 45\degree$, (c) $R_0 = 6$ kpc, and (d) $t = 1.34$ Gyr.
Fig. 6. Same as figure 4, but for the line-of-sight velocity normalised to 180 km s$^{-1}$. Schematic tracers of peculiar features (lines) and terminal velocity tangency (squares) are shown. See the text (subsection 4.1) for the labeled lines and boxes.

Following the interpretation by Bissantz et al. (2003), the 3-kpc arm would correspond to the gaseous arm colored in blue in figures 7a,b. Therefore, our result supports the interpretation by Fux (1999). The near part of the offset ridge is the one colored red, which could be due to a part of the “Connecting arm” (C). Therefore, the clumpy nature in this arm means that the offset ridge of the Milky Way galaxy can consist of some gas clumps. Contrary to Fux (1999), “135-km s$^{-1}$ arm” (D) is a part of the far side of the bar end in our model. We note, however, that the above arguments concerning this comparison between corresponding structures in our model and observations is qualitative, because our current “barred” galaxy is somewhat smaller than the Milky Way, resulting in a lower rotational velocity at 8 kpc of 163 km s$^{-1}$ compared to ∼220 km s$^{-1}$.

The cold gas in the galactic center (< 200 pc, the one colored by purple) corresponds to the feature known as CMZ in the observed CO $l$–$v$ diagram. However, it is not clearly seen in our $l$–$v$ diagram model, compared to that in the Milky Way galaxy. Concerning the mass modeling, this may be attributable to differences in the bar parameters between our model and the galactic bar, but also to the absence of a central bulge. It is known that bar parameters, such as the pattern speed and axis ratio, can affect the gas inflow rate and shape of dust lanes, and thereby influence the formation of the CMZ (Athanassoula 1992; Englmaier & Gerhard 1997; Patsis & Athanassoula 2000). According to these previous studies, the galactic bar may be rounder or more concentrated than the bar obtained in our simulation. Another discrepancy between our model and the Milky Way is that stellar number counts show evidence for the existence of an inner bar in the Milky Way, which is much smaller than the outer bar (or triaxial bulge) with a semi-major axis of 3.5 kpc (Alard 2001; Nishiyama et al. 2005). However, our model does not have nested stellar bars. Rodriguez-Fernandez and Combes (2008) suggested that the parallelogram shape of the $l$–$v$ diagram of the CMZ is due to the influence of this inner bar (also known as nuclear bar or secondary bar). The central bulge, which is not included in the initial condition of the present model, may also affect the dynamics of the central region. A more detailed comparison between the observed kinematics of the gas and models in the central several degrees requires a high numerical resolution in the central part in numerical models. The effects of the central bulge and bar properties on the kinematics will be discussed in the high-resolution models elsewhere.

In terms of realistic modelling heating physics of the ISM, we need to model the spatial dependence of the incident FUV, which has been assumed to be constant ($G_0 = 1.0$) everywhere in this paper [see equation (4)]. Gerritsen and Icke (1997) calculated the incident FUV by summing the FUV flux from all stars according to their ages. The resultant radiation field declines outside the stellar disk with the galacto-centric distance, as $1/R^2$. This means that the incident FUV is stronger in the central region than that in the solar neighborhood,

3 There is a discussion on the existence of the inner bar in the Milky Way. At the central region, the magnitude differences in the star counts on both sides are less than 0.1 mag, so effects from asymmetric dust absorption will cause quite some uncertainty in the interpretation of the star counts. However, observations of external barred galaxies shows that many barred galaxies have inner bars (e.g., Erwin 2004).
implying that if we were to consider the spatial dependence of the incident FUV in our model, for example, \( G_0 \propto 1/R^2 \), then the consumption of gas by star formation in the region of the CMZ might be suppressed, yielding a stronger CMZ present in our \( l-v \) diagram.

### 4.2. Clumpy Morphology

In figures 7c and 7d, we have marked gas clumps \( (> 10^5 M_\odot) \) with the same color between the face-on map and \( l-v \) diagram. We here define the gas clumps by using a Friend-of-Friend (FOF) method (Davis et al. 1985) with a linking length of 30 pc for the cold gas. The large-scale peculiar features, such as the “Connecting arm” (C), “3-kpc = arm” (E), and “135-km s\(^{-1}\) arm” (D) in \( l-v \) diagram, are actually ensembles of dense clouds and filaments.

It is known that the Bania’s “Clump 1” and “Clump 2” are placed around the negative longitude end of the 135 km s\(^{-1}\) arm and at the positive longitude side of the CMZ in observed CO \( l-v \) diagram (Bania 1977; Bania et al. 1986; Stark & Bania 1986). We associate these clumps with clumps “c1” and “c2” in figures 7c and 7d, respectively. The mass of clump “c1” is \( \sim 10^5 M_\odot \), and clump “c2” is \( \sim 5 \times 10^5 M_\odot \). From the time evolution of these clumps, we found that clumps “c2” eventually collapsed into the galactic center. Other gas clumps within a bar region tend to spiral into the galactic center while losing their angular momenta around their orbital apocenters via collisions between them. Fux (1999) inferred that Bania’s clump 2 and another vertical feature near the clump could correspond to

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**Fig. 7.** (Left panels) Correspondence between the gaseous spiral arms in the \( x-y \) plane and the \( l-v \) features for cold gas in the inner galaxy at \( t = 1.24 \) Gyr. (a): Spatial distribution on the \( x-y \) plane. (b): \( l-v \) diagram. Each SPH particle is plotted as a dot in spite of its distance. The observer is located at \((R_0, \phi_0) = (8 \text{ kpc}, 25^\circ)\), represented by the \( \odot \) mark point in the top panel, and has pure circular motion. (Right panels) Same as the left panels, but colored for gas clumps. The solid curves labeled by “C”, “D”, and “E” correspond to them in figure 6. The open circles (c1 and c2) are examples of gas clumps around their apocenters of orbits.
gas clumps that are just going to cross the near-side offset axis (i.e., connecting arm). Contrary to this picture, we here suggest that the vertical features in the observed CO \( l-v \) diagrams near the CMZ are streams of gas clumps spiraling into the galactic center. As a consequence, our simulation suggests that gas is stochastically supplied into the galactic central region by dense gas clumps.

### 4.3. The Non-Stationarity of \( l-v \) Features

We have found that the observed \( l-v \) diagram is reproduced only at a specific time \((t \sim 1.24 \text{ Gyr})\), and that features change on a time-scale of \( \sim 100 \text{ Myr} \), suggesting that the observed \( l-v \) features are transient features. The non-stationarity was also found by Fux (1999) and Bissantz et al. (2003) in their numerical models. Fux (1999) and Bissantz et al. (2003) attributed the non-stationarity to the wandering of a stellar bar around the center of mass, and the difference of the pattern speeds between the stellar bar and the spiral arms, respectively. In fact, our model shows that the stellar spiral arms rotate more slowly than the bar (figure 3b), suggesting that decoupling between the stellar bar and spirals may cause the non-stationarity.

Recently, Baba et al. (2009) analyzed the kinematics of star-forming regions in using the same numerical model discussed in this paper with the observed proper motions of maser sources in the Milky Way. They suggested that the galactic stellar spiral arms should be transient, recurrently formed structures, rather than the “stationary” density waves proposed in Lin and Shu (1964) (for a review, see Bertin & Lin 1996). This transient nature of stellar spirals is also supported by previous \( N \)-body simulations of stellar disks without the ISM (Sellwood & Carlberg 1984; Sellwood 2000, 2010; Fujii et al. 2010). We infer that the dynamic nature of stellar spiral arms, themselves, could contribute to the non-stationarity of the \( l-v \) diagram. We will quantitatively investigate a driving mechanism of the non-stationarity in our following paper.

### 5. Conclusions

By using a high-resolution, \( N \)-body + hydrodynamical simulation in which the multi-phase ISM, star-formation, and SN feedback were self-consistently taken into account, we qualitatively reproduced not only large-scale structures of the \( \text{H} \text{i} \) and CO \( l-v \) diagrams, such as the terminal velocity tangent points and the coherent features, but also clumpy structures. Previous studies with numerical simulations on \( l-v \) diagrams did not reproduce these clumpy structures. When we adopt a model galaxy whose velocity is similar to the Milky Way galaxy with the same numerical method, we can advance our argument more qualitatively. We will show the results in the near future.

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