Multi-Phase Gas Dynamics in a Weak Barred Potential

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Abstract

The structure of the interstellar medium in the central kpc region of a galaxy with a weak bar-like potential is investigated taking into account realistic cooling and heating processes and the self-gravity of the gas. Using high resolution hydrodynamical simulations, it is revealed that the resonant structures (e.g. smooth spiral shocks and a nuclear ring) are very different from those seen in past numerical models where simple models of the ISM, i.e. non-self-gravitating, isothermal gas were assumed. We find that the pc-scale filaments and clumps form large scale spirals, which resemble those seen in real galaxies. The fine structures are different between the arms and in the nuclear region. The next generation millimeter interferometer (ALMA) may reveal the fine structures of the cold gas in nearby galaxies.

We also find a large scale anisotropy in the gas temperature, which is caused due to non-circular velocity field of the gas. The damped orbit model based on the epicyclic approximation explains the distribution of the hot (> $10^4$ K) and cold (< 100 K) gases appearing alternately around the galactic center. Because of the temperature anisotropy, cold gases observed by molecular lines do not necessarily represent the real gas distribution in galaxies.

Position-Velocity diagrams depend strongly on the viewing angles. As a result, the rotational velocity inferred from the PV maps could be two times larger or smaller than the true circular velocity.

Key words: interstellar matter — galaxies — gas dynamics

1. INTRODUCTION

Gaseous response to the bi-symmetric gravitational potential, such as a stellar bar in galaxies, has been well studied numerically since early 70’s (Miller, Prendergast, & Quirk 1970; Sorensen, Matsuda, & Fujimoto 1976; Matsuda & Nelson 1977; Huntley, Sanders, & Roberts 1978; Matsuda & Isaka 1980; van Albada & Roberts 1981; Schwarz 1984; Matsuda et al. 1987; Athanassoula 1992; Wada & Habe 1992; Friedli & Benz 1993; Wada & Habe 1995; Piner, Stone, & Teuben 1995; Heller & Shlosman 1994; Engliemaier & Gerhard 1997; Fukuda, Wada & Habe 1998; Fux 1999; Patsis & Athanassoula 2000; Engliemaier & Shlosman 2000; Fukuda, Habe, & Wada 2000). A rotating bar-like potential causes resonances in gas orbits, and spiral-like density enhancement or shocks are formed in the gas disk. However, almost all simulations and analyses in the past three decades assumed a simple model of the interstellar medium (ISM) with the isothermal equation of state, where the gaseous temperature is assumed a $\sim 10^4$ K. In some models, the energy equation is solved, but $10^4$ K cutoff is introduced (Friedli & Benz 1993). In another major numerical representation of the ISM, i.e. the “sticky particle” method or cloud-fluid model (Combes & Gerin 1985; Fukunaga & Tosa 1991), the ISM particles lose their energy via inelastic collisions, and the velocity dispersion of the particles are kept roughly constant. The isothermal equation of state or constant velocity dispersion would be a relevant approximation to investigate the global gas dynamics in galaxies. It is obvious, however, that the interstellar matter is not an isothermal and uniform media (McKee & Ostriker 1977), the inhomogeneous nature of the ISM should be taken into account to investigate gas dynamics in a local scale or on a galactic central region. In the case that we have no observational information about the ISM with fine enough spatial resolution (e.g. parsec scale) in external galaxies, the simple treatment of the ISM is enough to compare the models with observations. Hopefully we will have extremely high quality observations on the ISM in the next decade. High resolution observations with the next generation millimeter/submillimeter interferometer (e.g. ALMA) will reveal the molecular gas structure with a hundred times finer spatial resolution. Therefore more realistic treatment of the ISM in simulations on a galactic scale is necessary to understand the ISM through comparison with the observations.

Recently Wada & Norman (1999, 2001) have investigated dynamics and structure of a self-gravitating gas disk in the central kpc region of a galaxy, taking into account realistic cooling ($10^4 K < T_g < 10^8 K$) and heating. Using
We solve the following equations numerically on a rotating frame of a bar potential in two dimensions.

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \]  
\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \frac{\nabla \rho}{\rho} = -\nabla \Phi_{\text{ext}} - \nabla \Phi_{\text{sg}} \]  
\[ \frac{\partial E}{\partial t} + \frac{1}{\rho} \nabla \cdot \left[ (\rho E + p) \mathbf{v} \right] = \Gamma_{\text{UV}} - \rho \Lambda(T_g), \]  
\[ \nabla^2 \Phi_{\text{sg}} = 4\pi G \rho, \]  

where, \( \rho, p, \mathbf{v} \) are density, pressure, and velocity of the gas, the specific total energy \( E \equiv |\mathbf{v}|^2/2 + p/(\gamma - 1)\rho \) with \( \gamma = 5/3 \), and \( \Omega_b \equiv |\Omega_b| \) is the pattern speed of the bar potential.

The potential of the analytical models is

\[ \Phi_{\text{ext}}(R, \phi) = \Phi_0(R) + \Phi_1(R, \phi), \]  

where \( \Phi_0 \) and \( \Phi_1 \) are axisymmetric and non-axisymmetric potentials, respectively. We use the ‘Toomre disk’ potential for the axisymmetric part. The potential has two parameters \( a \) (scale parameter called ‘core radius’) and \( v_{\text{max}} \) (the maximum rotation speed), and expressed as

\[ \Phi_0(R) = \frac{c^2}{a(R^2 + a^2)^{1/2}}, \]  

where \( c \) is given as \( c \equiv v_{\text{max}}(27/4)^{1/4}a \). The non-axisymmetric part of the potential is assumed to be in the form

\[ \Phi_1(R, \phi, t) = \varepsilon(R) \Phi_0 \cos(2(\phi - \Omega_b t)), \]  

where \( \varepsilon(R) \) is given as

\[ \varepsilon(R) = \varepsilon_0 \frac{aR^2}{(R^2 + a^2)^{3/2}}. \]  

The parameter \( \varepsilon_0 \) represents the strength of the bar. This formalism is taken from Sanders (1977). The parameter \( \varepsilon_0 \) is at full strength from the beginning of simulations. Since our bar models are weak (\( \varepsilon_0 = 0.05 \), i.e. \( \Phi_1/\Phi_0(a) = 0.02 \)), initial strong shocks and subsequent accretion of gas to the galactic center do not occur.

The equations (1), (2), and (3) are solved by second-order AUSM (Advection Upstream Splitting Method) based on Liou & Steffen (1993). We achieve third-order spatial accuracy with the Monotone Upstream-Centered Schemes for Conservation Laws (MUSCL) approach (van Leer 1977).

Time integration is achieved by the second-order leapfrog method. Each time step is determined by the Courant condition. We adopt implicit time integration for the cooling term.

Various two-dimensional test problems, such as the double Mach reflection of a strong shock, a point explosion in an adiabatic uniform medium, an isothermal gas flow in a weak barred potential, and evolution of spiral gravitational waves in a differentially rotating disk are described in Wada & Norman (2001). We find that AUSM with
MUSCL is as powerful a scheme for astrophysical problems as PPM (Woodward & Colella 1984), but the algorithms and coding are much simpler than PPM.

We use 2048 grid points for calculating gas dynamics in a 2 kpc x 2 kpc region which includes the galactic center. Therefore the spatial resolution is 0.98 pc. The gravitational potential of the gas is calculated using the convolution method with the Fast Fourier Transform (Hockney & Eastwood 1981). In this method, 4096 grid cells and a periodic Green's function are used to calculate the self-gravity of the isolated matter in the 2048 grid points.

We also assume a cooling function \( \Lambda(T_g) \) \( (10 < T_g < 10^8 \text{ K}) \) and the photoelectric heating rate \( \Gamma_{\text{UV}} \). We use the cooling curves of Spaans & Norman (1997) (Fig. 1 in WN01). The cooling processes taken into account are, (1) recombination of H, He, C, O, N, Si and Fe, (2) collisional excitation of HI, CI-IV and OI-IV, (3) hydrogen and helium bremsstrahlung, (4) vibrational and rotational excitation of H2 and (5) atomic and molecular cooling due to fine-structure emission of C, C+ and O, and rotational line emission of CO and H2. We assume solar metallicity in this paper.

We assume a uniform UV radiation field and photoelectric heating of grains and PAHs. The heating rate \( \Gamma_{\text{UV}} \) is the same as in Gerritsen & Icke (1997): \( \Gamma_{\text{UV}} = 1.0 \times 10^{-24} \varepsilon G_0 \text{ergs s}^{-1} \), where the heating efficiency \( \varepsilon \) is assumed to be 0.05 and \( G_0 \) is the incident FUV field normalized to the local interstellar value.

The initial condition is an axisymmetric, uniform and rotationally supported disk, whose radius is 1 kpc, with the total gas mass \( 5 \times 10^7 M_\odot \) which is about 2% of the total mass determined by the background gravitational potential. The initial rotational velocity is chosen in order to balance the centrifugal force caused by the external potential \( \Phi_{\text{ext}} \) and \( \Phi_{\text{gr}} \).

Random density fluctuations are added to the initial disk, with an amplitude less than 1% of the unperturbed density and temperature. The initial temperature is set to \( 10^3 \text{ K} \) over the whole region. In ghost zones at boundaries, the physical values remain at their initial values during the calculations. From test runs, we found that these boundary conditions are much better than so called ‘outflow’ boundaries, because the latter cause strong unphysical reflection of waves at the boundaries.

3. NUMERICAL RESULTS

3.1. Non-isothermal, self-gravitating gas in a bar potential

For comparison with the realistic model, we first show the density and temperature distribution of a model without taking into account self-gravity of the gas in Fig. 1, which is a snapshot at \( t = 20 \text{ Myr} \) (about 2.4 rotational period at \( R = 0.2 \text{ kpc} \)). The surface density map (Fig. 1(a)) shows a typical gas response to a weak bar potential with two inner Lindblad resonances (IILR and OILR). The two inner leading spirals form an oval structure. The outer two-arm trailing spiral is a consequence of the OILR (Wada 1994). The temperature map (Fig. 1(b)) shows a quadruple distribution. The gas is heated up to \( 10^4 \sim 10^5 \text{ K} \) at upstream sides of the leading and the trailing spirals. At downstream regimes, the gas temperature is as low as the lower limit of the temperature (10 K) to the contrary. This extreme anisotropy is because the advective cooling/heating that dominates the heat balance in the supersonic non-axisymmetric flow. See details in §3.2.

If we take into account self-gravity of the gas, however, the density and temperature distributions in a quasi-stable state have very different fine structures from Fig. 1. Figure 2 shows density and temperature maps of the self-gravitating model at \( t = 61 \text{ Myr} \). As seen in the density map (Fig. 2(a)), the clumpy and filamentary dense gases form weak spiral density enhancements, whose location roughly coincides with those in the non-self-gravitating model. The cold gases form complexes of clouds in the spirals that look similar to the giant molecular clouds in spiral galaxies.

The complicated network of the filaments and clumps on a local scale is the same as that in axisymmetric models in WN01. A number of processes are involved in the formation of the filamentary structure: 1) tidal and collisional interactions between dense regions formed due to the thermal and gravitational instabilities, 2) differential rotation, and 3) shear motion due to local turbulent motion.

The closeup of the central 500 pc region reveals the fine structure of the gas (Fig. 3(a)). The dense clumps in the nuclear region are typically 20-50 pc across, and their masses \( \sim 10^5 M_\odot \). The filamentary structures, which are nearly parallel to the bar major axis, are prominent. They are formed due to non-axisymmetric motion and shear in this region. The density range is greater than four orders of magnitude. On other hand, the closeup of the arm region (Fig. 3(b)) shows that its fine structure is very different from that in the nuclear region. The size of the dense clumps in the arms is smaller than that in the central region, because the velocity dispersion is smaller in the arm regions. This result suggests that the star formation processes in the arm and in the central regions would be different.

Comparing the realistic ISM model (Fig. 2) with the non-self-gravitating model (Fig. 1), the continuous galactic shocks seen in the non-selfgravitating model, is no longer seen in the realistic model. Spiral structures are actually ensembles of dense clouds and filaments. The continuous central ring seen in Fig. 1 is not also reproduced in the self-gravitating model, where the central density structure is very complicated as seen in Fig. 3 (a). These results suggest that self-gravity of the gas should not be negligible even if the gas mass fraction to the dynamical mass is small (2% in the present case), in order to explore the gas dynamics in the central kpc region of galaxies. The isothermal approximation for the ISM, which was often used in past numerical simulations, would be relevant for a galactic scale gas dynamics, but more realistic treatment of the cooling processes should be necessary for the ISM on a smaller scale. We should take into account small
scale structure of the ISM especially for the cases that star formation and its energy feedback to the ISM are important. If one uses the isothermal gas model for the ISM with star formation, it is hard to avoid to introduce some phenomenological models for the star formation and energy feedback processes. Our numerical approach, which is based on the basic equations that represent the phenomena, is less ambiguous in terms of these points.

3.2. Effect of the advective cooling in a non-uniform stream motion in a bar potential

We mentioned in the previous section that temperature of the gas in a bar potential changes quadruply on a global scale, i.e. cold ($T_{g} \lesssim 100$ K) and hot ($T_{g} \gtrsim 10^{4}$ K) regimes appear alternately around the galactic center (Fig. 1(b) and 2(b)). This is because the advective cooling/heating dominates the heat balance in this system. This can be explained analytically using the “damped gas orbit model” under the epicycle approximation.

Wada (1994) provided an analytical representation which represents the behaviour of a non-self-gravitating gas in a rotating bar-like potential. Its outline is as follows. The gas dynamics can be understood in terms of closed elliptical orbits which are solutions to the equations of motion of a forced-damping oscillator driven by a periodic external force. Gaseous elliptical orbits always incline to the bar potential in a leading sense inside of the corotation, and in a following sense outside of the corotation. If there are two ILRs, the gas orbits at the ILRs are oriented by $45^\circ$ with respect to the bar potential. The damped orbits gradually change their orientation with their radius. Since the direction of the gradual rotation near to the first ILR and that near to the second ILR are in an opposite sense, leading or trailing spiral-like enhancements appear around the first and the second ILR, respectively. This gradual rotation is explained in terms of the phase-shift of a damping oscillator. The analytical model well describes the gas behaviour seen in hydrodynamical simulations.

Under the epicycle approximation, the simplest way to represent the effect of the gaseous nature, such as viscosity, on closed orbits is to introduce a simple damping term, which is proportional to the velocity of the radial oscillation $2\Lambda R_{1}$ into the equation of motion.

$$\dot{R}_{1} + 2\Lambda \dot{R}_{1} + \kappa_{0}^{2} R_{1} = f_{0} \cos 2(\Omega - \Omega_{b}) t,$$

where

$$f_{0} = -\left[\frac{d\Phi_{b}}{dR} + \frac{2\Omega \Phi_{b}}{R(\Omega - \Omega_{b})}\right]_{R_{0}},$$

and $\Lambda$ is the damping rate. This equation describes a radial damped oscillation at around $R_{0}$, which is driven by an external periodic force at a frequency of $2(\Omega - \Omega_{b})$. The general solution to this equation is

$$R_{1}(t) = A e^{-\lambda t} \cos(\omega t + \alpha) + B \cos[2(\Omega - \Omega_{b}) t + \delta_{0}],$$

where $A$ and $\alpha$ are arbitrary constants, and $\omega \equiv \sqrt{\kappa_{0}^{2} - \lambda^{2}}$. The first term of the right-hand side of (11) is a general solution of a harmonic oscillator having a natural frequency of $\omega$ with weak friction. Amplitude $B$ and the phase-shift, $\delta_{0} \equiv \delta(R_{0})$, are

$$B = \frac{f_{0}}{\sqrt{\{\kappa_{0}^{2} - 4(\Omega - \Omega_{b})^{2}\}^{2} + 16\lambda^{2}(\Omega - \Omega_{b})^{2}}}$$

and

$$\delta_{0} = \arctan \left[\frac{2F\Theta}{F^{2} - 1}\right],$$

where

$$F = 2(\Omega - \Omega_{b})/\kappa_{0}, \quad \Theta \equiv \lambda/\kappa_{0}.$$

The phase-shift $\delta_{0}$ is always negative if $F > 0$, and $\delta_{0} = -\pi/2$ when $F^{2} = 1$, that is, at the Lindblad resonances ($\Omega = \Omega_{b} \pm \kappa_{0}/2$). The negative $\delta_{0}$ means that the damping oscillation is delayed from the periodic driving force. Since the first term on the right-hand side of equation (11) is a damping term which does not represent a closed orbit, we ignore it. Using $\phi_{0}(t) = (\Omega - \Omega_{b}) t$, we obtain a closed orbit ($R_{1} , \phi_{1}$),

$$R_{1}(\phi_{0}) = B \cos(2\phi_{0} + \delta_{0}),$$

and

$$\phi_{1}(\phi_{0}) = -\frac{\Omega_{b} B}{R_{0}(\Omega - \Omega_{b})} \left[\sin(\delta_{0}) - \sin(2\phi_{0} + \delta_{0})\right] - \frac{\Phi_{b}(R)}{2R_{0}^{2}(\Omega_{b} - \Omega_{b})^{2}} \sin(2\phi_{0}).$$

We plot the orbits for the bar potential,

$$\Phi_{\text{bar}} = (R^{2} + b^{2})^{-1/2} \left[1 + \varepsilon_{0} b R^{2}(R^{2} + b^{2})^{-3/2}\right]$$

with $\varepsilon_{0} = 0.05, b = 0.5, \Omega = 0.25, \lambda = 0.1$ in Fig. 4.

The gas velocity field $(v_{R}, v_{\phi})$ is obtained from (15) and (16):$

$$v_{R}(R_{0}) = -B(\Omega - \Omega_{b}) \sin(\phi_{0} + \delta_{0}),$$

$$v_{\phi}(R_{0}, \phi_{0}) = \left[ R_{0} + B \cos(\phi_{0} + \delta_{0}) \right] \left[ -\frac{2\Omega_{b} B}{R_{0}} \cos(2\phi_{0} + \delta_{0}) - \frac{\Omega_{b}(R_{0})}{R_{0}^{2}(\Omega_{b} - \Omega_{b})} \cos(2\phi_{0}) \right].$$

Now, the energy equation in the hydrodynamical simulations can be written as

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho H}{\partial x} + \frac{\partial \rho H}{\partial y} = \rho \Gamma_{UV} - \rho^{2} \Lambda(T_{g})$$

where specific enthalpy $H = E + p/\rho$ with $E = |v|^{2} + p/(\gamma - 1)\rho$.

The advective cooling/heating rate is about one order of magnitude larger than the radiative cooling/heating rate in the supersonic gas disk that we are exploring. If the radiative cooling and heating is in an equilibrium (i.e., the right-hand side of eq. (20)), temperature change in a unit time due to the advective terms can be written as

$$\Delta T_{\text{ad}}(R, \phi) \sim -\frac{\mu m_{H}(\gamma - 1)}{k_{B}} \left[\frac{\partial |v|^{2}}{\partial R} - \frac{\partial |v|^{2}}{R \partial \phi}\right] \left[\partial |v|^{2}/\partial R + \partial |v|^{2}/R \partial \phi\right],$$

$$\sim 1500 \left[\frac{\partial |v|^{2}}{\partial R} + \frac{\partial |v|^{2}}{R \partial \phi}\right] K \text{Myr}^{-1},$$

(21)

(22)
where \( v^2 \gg c_s^2 \) and \( \rho \sim \text{const} \) is assumed for simplicity. Using (18) and (19), we plot \( -\partial |\mathbf{v}|^2/\partial R + \partial |\mathbf{v}|^2/R \partial \phi \) in Fig. 5. \( \Delta T_{\text{ad}} \) is about \( \pm 10^{-3} - 10^{-4} \) K Myr\(^{-1}\). The quadrupole anisotropy of the advective cooling and heating in the hydrodynamical simulations (Fig. 1 and 2) is well reproduced, and it suggests that the non-axisymmetric velocity field of the gas dominates the global temperature distribution in a weak barred potential.

4. OBSERVATIONAL IMPLICATIONS

From the numerical results shown in §3.1, we can infer how the molecular gas in nearby galaxies is observed with the submillimeter interferometers. It is crucial to treat realistically the cooling and heating processes of the ISM, especially when one tries to compare the numerical result with observations, such as molecular line observations. As shown in §3.1, the temperatures in the ISM in a bar potential globally anisotropic. This is essential to interpret the observed molecular line intensity distribution. To make detailed comparison between the models and observations, one needs radiative transfer calculations for molecular lines (see Wada, Spaans, & Kim 2000 for the Large Magellanic Clouds). Alternatively, we can use the density of the cold gas \( (T_g < 100 \) K) component instead of the line intensity derived from detail line transfer calculations in order to infer the observed molecular gas distribution.

Figure 6 (a) is the surface density distribution of the cold gas \( (< 100 \) K) with a 100 pc resolution. One may regard this map as a “CO integrated intensity map” of a galaxy in the Virgo cluster observed with the Nobeyama Millimeter Interferometer, for example. Two clumpy trailing spirals are clearly seen, and one might see a nuclear “pseudo ring”. There are dense regions at the base of the spirals and also at the nuclear region. Figure 6 (b) is the same as Fig. 6 (a), but with 10 pc resolution. It is clear that spirals are actually an ensemble of small clumps and filaments (see also Fig. 2(b)). Comparison of the two ‘observations’ suggests that spatial resolution of the present-day interferometers are still too coarse to discuss small scale \( (100 \) pc) structure of the cold gas in nearby galaxies. In other words, one should not be confused by the small scale inhomogeneity, which are comparable to the beam size, seen in observed intensity maps.

The other important implication from our numerical results is that distribution of the cold gas derived from molecular line intensity \( (\text{e.g. CO (1-0)}) \) does not necessarily represent true mass distribution of the gas even on a galactic scale. The advective cooling and heating of the gas due to the non-circular velocity field in a bar potential dominate global distribution of the gaseous temperature. Suppose there is a uniform gas ring between the IILR and OILR. The temperature of the gas ring is roughly divided into two hot \( (T_g > 10^4 \) K) and two cold \( (T_g < 100 \) K) regions. Therefore we cannot observe gases in the hot regions with the CO (1-0) lines, for example, and non-axisymmetric distribution of the gas is apparently observed. A “hidden” hot gas component coexists with the nuclear “pseudo-ring” seen in Fig. 6 (a).

In order to resemble the observed position velocity (PV) maps for the molecular gas, we have convolved the numerical result (Fig. 2) with different ‘beam sizes’ and velocity resolutions (Fig. 7 and 8). The PV maps obtained for three different viewing angles are shown. From comparison between the three figures, one can find that the PV map strongly depends on the viewing angles (\( \theta_v \)). Along the bar major axis \( (\text{i.e. } \theta_v = 0^\circ) \), about two times larger line-of-sight velocity than the true circular rotational velocity (the dashed curve) is apparently observed. If we observe the same model along the minor axis of the bar \( (\text{i.e. } \theta_v = 90^\circ) \), the PV diagram represents nearly rigid rotation, and the apparent circular velocity is about a half of the real circular velocity at the core radius \( (R \sim 200 \) pc). Therefore if one observes the ISM in a edge-on galaxy that has a weak bar, and evaluate the dynamical mass from the rotation curve, then the mass could be four times larger or smaller than the real mass, depending on the viewing angle. This viewing angle effect originating in non-circular gas motion has been also known in previous isothermal simulations (Wada et al. 1994; Athanassoula & Bureau 1999). More quantitative analysis of the effect of non-circular motion on the rotation curves is discussed in Koda & Wada (2001).

Figure 8 is the same as Fig. 7, but with low spatial and velocity resolution \( (100 \) pc and 5 km s\(^{-1}\) which resembles the observations with millimeter interferometers such as Nobeyama Milliliter Array. Although the surface density map does not reveal the fine structure of the cold gas, the low resolution PV map represents basically the same kinematical feature of the system. The most notable difference between the high and low resolution PV maps is that there are high ‘intensity’, steep velocity components \( (\Delta v \sim 50 - 100 \) km s\(^{-1}\)) in the high resolution map. These features are caused by the local non-circular motion. Most prominent examples are seen in the central region \( (R < 100 \) pc) in the PV map \( (\theta_v = 0^\circ \text{ and } 45^\circ) \) of Fig. 7. These features are originated from filamentary structures along the bar major axis seen in the density map. Such features cannot be resolved as discrete components in the low resolution PV map (Fig. 8). Therefore, in the low resolution PV maps, one might interpret the rotation curve steeply rises near the galactic center. One should note that even the bar potential assumed here is very weak \( (\Phi_1/\Phi_0 < 0.02) \), the non-circular motion of the gas is large enough to cause the viewing angle effect on the PV diagrams as seen in Fig. 7 and 8.

5. CONCLUSIONS

The parsec-scale structure of the interstellar medium (ISM) in the central kpc region of a galaxy with a weak bar-like potential is discussed based on our two dimensional, high resolution hydrodynamical simulations, taking into account realistic cooling and self-gravity of the gas. The results and conclusions are summarized as follows.
• Taking into account realistic cooling/heating processes and self-gravity of the gas, the smooth spiral shocks which appear in the non-self-gravitating, isothermal gas model are not formed in the ISM.

• The resonant structures due to the inner Lindblad resonances, such as spirals, have actually parsec-scale fine structures, which are filamentary and clumpy dense gases (§3.1; Fig. 2). The fine structures are different between the arms and the nuclear region (§3.1; Fig. 3).

• There is large scale anisotropy of the gaseous temperature, which is due to the non-circular velocity field of the gas (§3.1; Fig. 1 and 2). The damped orbit model based on the epicycle approximation explains the quadratic distribution of the hot (> 10^4 K) and cold (< 100 K) gases around the galactic center (Fig. 4 and 5).

• Because of the temperature anisotropy, cold gases observed by molecular lines do not necessarily represent all gas components even on a global scale (§3.2; Fig. 6).

• Position-Velocity (PV) diagrams depend strongly on the viewing angles even if the bar component is very weak. The line-of-sight velocity inferred from the PV maps along the major axis of the bar potential is about four times larger than that along the minor axis (§4; Fig. 7 and 8).

• PV diagrams obtained using the same spatial and velocity resolutions in the present millimeter interferometers globally show the same kinematics of the gas with ten times finer resolutions. However, the low resolution PV maps do not reveal the fine velocity structure, and as a result, steeply rising rotation curves near the galactic center (R ≲ 100 pc) can be apparently observed (§4; Fig. 7 and 8).

• The spatial resolution of the present millimeter interferometers for external galaxies are not fine enough to discuss the gas dynamics on a hundred parsec scale, and we should wait for the next generation radio interferometers, e.g. ALMA (Fig. 6).

Most numerical simulations on the gas dynamics in a non-axisymmetric gravitational potential in the last three decades have assumed the simple model of the ISM. Under such approximation, the gas dynamics is well understood theoretically. However, we should investigate again the dynamics and structure of the ISM in galaxies using more realistic model based on the relevant basic equations.

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Fig. 1. (a) Density distribution of a model without self-gravity of the gas. The major-axis of the weak bar potential of a pattern speed, $\Omega_b = 140 \text{ km s}^{-1} \text{ kpc}^{-2}$ is horizontally fixed. 512 × 512 grid points are used. Color represents log-scaled density between 1 and $10^3 M_\odot \text{ pc}^{-2}$. Gas rotates counter clockwise. Inner Lindblad Resonances are located at $R = 0.2$ and 0.4 kpc. (b) Same as (a), but for temperature between 10 and $10^5$ K.

Fig. 2. Same as Fig. 1, but self-gravity of the gas is taking into account. 2048×2048 grid points are used.

Fig. 3. (a) Close-up of the central 500 × 500 pc region in the same model of Fig. 2. The color scale represents log-scaled density between 0.1 and $10^3 M_\odot \text{ pc}^{-2}$. (b) Arm-region

Fig. 4. Gas orbits under the influence of the two ILRs, derived from the damped orbit model (eqn. (15) and (16)).

Fig. 5. Distribution of adiabatic cooling/heating rate,
$$\left[ \frac{\partial |v|^2}{\partial R} + \frac{\partial |v|^2}{R \partial \phi} \right].$$
See eqn. (22). Contours are drawn every 1 from -10 to 10. Solid/dotted lines represent heating/cooling regions.

Fig. 6. (a) Density distribution of the cold gas ($T_g < 100$ K) in a weak bar potential convolved with a 100 pc “beam” size. (b) Same as left, but with a 10 pc beam size. Unit of scale is kpc.

Fig. 7. Surface density distribution of the cold gas with 10 pc grid size and 1 km s$^{-1}$ for velocity resolution. Position-velocity diagrams from three viewing angles (0, 45, and 90 degree from the bar major axis) are plotted. The dashed curve is a rotation curve derived from the axisymmetric gravitational potential eq. (6).

Fig. 8. Same as Fig. 7, but with 100 pc and 5 km s$^{-1}$ spatial and velocity resolution.
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