1. INTRODUCTION

A standing spiral shock solution was first numerically discovered in the 1960s in a rotating gas disk in the galactic potential that had a tightly wound spiral perturbation (i.e., the “pitch angle” was very small). Since then, in most of the theoretical studies on the galactic “shock” (e.g., Fujimoto 1968; Roberts 1969; Woodward 1975; Johns & Nelson 1986; Lubow et al. 1986), the interstellar medium (ISM) has been treated as an isothermal and homogeneous fluid with a two-dimensional approximation, or it has been modeled as an $N$-body system of small cloudlets (e.g., Tomisaka 1986). Global evolution of the spiral shock was studied in the 1980s (Johns & Nelson 1986), using time-dependent, two-dimensional (2D) hydrodynamic simulations that showed that spiral shocks are stable and long-lasting for various pitch angles.

However, the steady, smoothed galactic shock does not consistently explain the complicated distribution of the ISM around spiral arms and the interarm substructures akin to the so-called spurs or feathers that are observed in real spiral galaxies (Elmegreen 1980; Scoville et al. 2001; Calzetti et al. 2005; La Vigne et al. 2006). Moreover, observed molecular clouds in galactic disks do not match the picture of hydrodynamic shocks in a uniform medium. It was, however, shown by full 2D global simulations of a non–self-gravitating, isothermal gas disk that the spurs are in fact natural consequences of the “wiggle” instability, which is caused by a purely hydrodynamic phenomenon: i.e., the Kelvin-Helmholtz instability (Wada & Koda 2004, hereafter Paper I). This phenomenon was also found by Shetty & Ostriker (2006). They also pointed out that the features only grow in the regions in the innermost several kiloparsecs if both self-gravity and magnetic fields are ignored. More recently, the three-dimensional (3D) response of the gas to the spiral potential was modeled using a local shearing box approximation in isothermal, MHD simulations that take self-gravity into account (Kim & Ostriker 2006), and these authors found that the wiggle instability is suppressed by the radial flapping motion of the shock.

These previous results suggest that hydrodynamic effects, the self-gravity of the gas, and magnetic fields play some important roles regarding the gas structures in a spiral potential. However, an important feature of the real ISM has been ignored: its inhomogeneous multiphase structures. Apparently the ISM is not an “isothermal fluid”; nevertheless, this is assumed to be the case in most hydrodynamic and MHD simulations. The effects of self-gravity and magnetic fields highly depend on the gaseous temperatures and phases. In this sense, an energy equation with realistic cooling and heating processes should be solved before taking these effects into account. The local box approximation with a shearing periodic boundary (e.g., Kim & Ostriker 2006) is not necessarily relevant for representing the dynamics of the multiphase ISM in galactic disks, because typical scales of the inhomogeneous structures of the ISM are not small enough compared to the disk size (cf. Wada & Norman 2001, 2007; Tasker & Bryan 2006). Moreover, since gravity is a long-range force, global 3D simulations for the whole disk are essential if self-gravity of the gas is to be considered. This is also necessary for the multiphase ISM, because the scale height and velocity dispersion are different for cold and hot gases. In 3D hydrodynamic simulations of self-gravitating gas disks that include the effects

\[ \text{ABSTRACT} \]

“Galactic shocks” (Fujimoto; Roberts) are investigated using full three-dimensional hydrodynamic simulations that take into account the self-gravity of the ISM, radiative cooling, and star formation followed by energy feedback from supernovae. This is an essential improvement over previous numerical models, in which two-dimensional isothermal, non–self-gravitating gas is assumed. We find that the classic galactic shocks are unstable and transient, and they shift to a globally quasi-steady, inhomogeneous pattern due to the nonlinear development of instabilities in the disk. The spiral patterns consist of many giant molecular cloud–like dense condensations, but those local structures are not steady, and they evolve into irregular spurs in the interarm regions. Energy feedback from supernovae does not destroy the quasi-steady spiral arms; rather, it mainly contributes to the vertical motion and the structures of the ISM. The results and methods presented here are a starting point for a more consistent treatment of the ISM in spiral galaxies, in which the effects of magnetic fields, radiative transfer, chemistry, and dynamical evolution of a stellar disk are taken into account.

Subject headings: ISM: kinematics and dynamics — ISM: structure — methods: numerical

Online material: mpeg animation
of radiative cooling, we should take the energy feedback from stars into account; otherwise the cold gas disk becomes unrealistically thin and the gravitational instability is strongly affected.

Here we show, for the first time, a 3D evolution of the ISM in a galactic spiral potential, taking into account a realistic radiative cooling effect and energy feedback from stars, especially from supernova explosions. The simulations are performed for the whole gas disk without any assumptions for symmetry. In order to ensure a high spatial resolution (10 pc), which is essential in order to reproduce the multiphase ISM, we here focus on the central part of a relatively small galaxy (radius 2.56 kpc; maximum circular velocity 150 km s$^{-1}$). However, this is a large enough region for us to see the global effect of the spiral potential on the inhomogeneous ISM. Our simulations clarify the apparent discrepancy between the steady solution of a "galactic shock" and the complicated, nonsteady structures of the ISM in real spiral galaxies. This is a major improvement over the previous simulations, and it will be a starting point for more realistic numerical models of the ISM that take into account the "lived" stellar potential and it will be a starting point for more realistic numerical models.

2. METHODS

The evolution of a gas disk (total mass $4.3 \times 10^9 M_{\odot}$; radius 2.5 kpc) in a fixed gravitational potential $\Phi_{ext}$ is solved by an Eulerian hydrodynamic method with a uniform Cartesian grid (Wada & Norman 2001; Wada 2001; Wada & Norman 2007). Here we briefly summarize the numerical scheme. We solve the following conservation equations and the Poisson equation in three dimensions, using $512 \times 512 \times 64$ grid points with a 10 pc resolution:

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

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} + \frac{\nabla p}{\rho} + \nabla \Phi_{ext} + \nabla \Phi_{sg} = 0,$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [(\rho E + p) \mathbf{v}] = \rho \Gamma_{UV} + \Gamma_{SN} - \rho^2 \Lambda(T_g),$$

$$\nabla^2 \Phi_{sg} = 4\pi G \rho,$$

where $\rho$, $p$, $\mathbf{v}$, and $\Phi_{sg}$ are the gas density, pressure, velocity, and self-gravitating potential of the gas, respectively. The specific total energy $E = \rho v^2/2 + p/(\gamma - 1)\rho$ with $\gamma = 5/3$.

We assume a cooling function $\Delta(T_g)$ (where 10 K $< T_g < 10^8$ K) with solar metallicity, photoelectric heating by dust ($\Gamma_{UV}$), and a uniform UV radiation field ($G_0 = 1.0$). The hydrodynamic scheme is the advection upstream splitting method (AUSM; Liou & Steffen 1993), with MUSCL (Monotone Upstream-centered Schemes for Conservation Laws). The Poisson equation is solved to calculate the self-gravity of the gas using the fast Fourier transform (FFT).

The external potential is given by $\Phi_{ext}(R, \phi, z) \equiv \Phi_0 + \Phi_1 + \Phi_2$ for

$$\Phi_0(R, z) \equiv a v_o^2 (27/4)^{1/2} (R^2 + a^2 + z^2)^{-1/2},$$

$$\Phi_1(R, z) \equiv b v_o^2 (27/4)^{1/2} (R^2 + b^2 + z^2)^{-1/2},$$

$$\Phi_2(R, \phi, z) \equiv \epsilon \omega b R^2 \Phi_1 [R^2 + b^2 + z^2]^{-3/2} \times \cos[2 \phi + 2 \cot(\phi) \ln(R/R_0)],$$

where $i$ is the pitch angle ($i = 10^\circ$) of the spiral potential, $R_0$ is an arbitrary constant, $a = 0.2$ kpc, $b = 2.5$ kpc, $v_o = v_b = 150$ km s$^{-1}$, and $\epsilon_0 = 0.1$. The pattern speed of the spiral potential is assumed to be $\Omega_p = 30$ km s$^{-1}$ kpc$^{-1}$. For comparison, we also run models with $\Omega_p = 15$ and 60 km s$^{-1}$ kpc$^{-1}$ and $\epsilon_0 = 0.05$. However, we find no essential differences in the conclusions (see also discussion in § 4).

We take into account two feedback effects of massive stars on the gas dynamics, namely, stellar winds and supernova explosions ($\Gamma_{SN}$). We first identify cells that satisfy the criteria for star formation. The criteria for each cell in which star formation is allowed are that (1) the gas density is greater than a threshold value; i.e., $\rho_{th,i} > \rho_i$; (2) the temperature is less than the critical temperature; i.e., $(T_i)_{th} < T_i$, and (3) criteria 1 and 2 are satisfied for 10$^5$ yr. Here we have chosen $T_i = 100$ K and $\rho_i = 600$ cm$^{-3}$. Assuming the Salpeter initial mass function with $m_h = 120 M_{\odot}$ and $m_l = 0.2 M_{\odot}$, we create test particles that represent massive stars ($\geq 8 M_{\odot}$). Typically, a few massive stars are replaced by one test particle. The initial velocity of each test particle is taken to be the same as that of its parent gas. The kinematics of the test particles in the external potential and the self-gravitational potential of the gas are followed by a second-order time-integration method. The stars (test particles) inject energy due to stellar winds into the cells in which they are located during their lifetimes, which are approximately 10$^5$ yr (Leitherer et al. 1992). When the star explodes as a supernova, an energy of 10$^{51}$ ergs is injected into the cell in which the test particle is located. A nonspherical 3D propagation of blast waves in the multiphase, nonuniform ISM is then followed consistently in the hydrodynamic simulations.

3. RESULTS

Figure 1 shows the time evolution of the density field on the $(x, y)$- and $(x, z)$-planes of the disk in the spiral potential. High-density gases form two-arm spirals, and there are also substructures, i.e., "spurs," between the spirals, as seen in real spiral galaxies (Elmegreen 1980). Each spur is a nonsteady structure, but spurs are always seen in our simulations (see also the mpeg animation available in the electronic edition of the Journal). As has been discussed in connection with previous 2D simulations (Paper I), each spur originates in a clump, whose size corresponds to the observational size of a giant molecular cloud, formed in the spiral arm. A small gradient of angular momentum in the clump is eventually enhanced, and the clump is stretched into the interarm region due to galactic rotation (see also Fig. 3). In the present model, the wiggle instability (see Paper I) is coupled with the gravitational and thermal instabilities. This causes a complicated distribution of the matter coupled with the galactic rotation and tidal shear motions. In spite of these complexities, pseudospiral patterns roughly associated with the spiral potential are always present. Energy feedback from supernovae (the average supernova rate is $\sim 0.2$ yr$^{-1}$) changes the local density and temperature of the ISM, but it does not significantly affect the global structures of the spirals in the galactic plane. Note that despite the complexity, the statistical structure of the density field (the probability distribution function of the density) is represented by a single lognormal function over a wide density range, as predicted by Wada & Norman (2007).

On the other hand, as shown in the right panels of Figures 1 and 2, the vertical distributions of density and temperature are strongly influenced by supernovae. Cold gases ($T_g < 100$ K), as well as hot gases ($T_g \sim 10^4$--$10^5$ K), are blown out from the disk plane to the halo, where warm ($T_g \sim 10^4$--$10^5$ K) media occupy most of the volume. The cold, dense gases sometimes form looplike structures and fall back to the disk. In the inner region, $r < 1$ kpc, where the supernova rate is higher than in the outer region, the halo gas is occupied mostly by the hot gases.
The interaction between the disk and halo that is revealed here is a numerical representation of a so-called galactic fountain or chimney (Shapiro & Field 1976; Norman & Ikeuchi 1989). In the original idea of the galactic fountain, hot gas is spouted up from the disk into the halo, where it cools and subsequently falls back to the disk. However, our results show that not only hot gases, but also cold, dense gases are spouted up. The vertical structure is not steady, but over a long timescale, the cold dense gas is distributed within ~100 pc from the galactic plane. The scale height of the gas is smaller in the central region due to the deeper gravitational potential, but the effects of a spiral potential to the vertical structure are not clearly seen.

Fig. 1.—Density distribution on the galactic plane (left) and the (x, z)-plane (right) at t = 104 and 206 Myr after the beginning of the simulation. The colors represent log-scaled density (in units of $M_\odot \text{pc}^{-3}$). The scale is in units of kpc. [This figure is available as an mpeg animation in the electronic edition of the Journal.]

Fig. 2.—Same as Fig. 1, but for the temperature distribution at $t = 155$ Myr. The colors represent log-scaled temperature (in units of K). The red regions indicate hot gases generated by supernovae.
In Figure 3, a velocity field in a disk plane \( z = 0 \) at \( t = 206 \) Myr is shown by streamlines overlaid on an isodensity surface.\(^4\) The streamlines are bent near the spiral arms, and they are spread into the interarm regions. One should note that the spurs at the interarm regions are not located along the streamlines, but rather are perpendicular to them. As has already been reported from 2D simulations (Paper I), the spurs move along the direction of the galactic rotation, but they are stretched by the spread flow. This implies that the observed spurs are not waves. It is also apparent from Figure 3 that the density and kinematic structures are highly irregular; therefore, they may not be represented by a local computational box with a periodic boundary. Global simulations, in which the whole galactic disk is calculated without assuming symmetry, are essential in order to understand the structure and evolution of the ISM on a kiloparsec scale.

The spiral structure seen in Figures 1–3 does not look like the typical hydrodynamic shock, in the sense that there is no clear jump of density, and it consists of nonsteady substructures. Figure 4 demonstrates the long-term evolution of density at \( r = 1.2 \) kpc. We see that hydrodynamic shocks are formed upstream (i.e., on the concave side of the spiral) of the minimum of the potential trough in the first 20 Myr or so. This is indeed the galactic shock solution found in the 1960s for a tightly wound spiral potential. However, these shocks do not stay at the initial positions, and they move back and forth between downstream and upstream of the potential minimum until \( t \approx 60 \) Myr. After this early oscillating phase, the “shocks” disappear, and a new state emerges that is characterized by its stochastic nature. The standing pattern near the potential minimum is a pseudospiral consisting of many clumps or parts of filaments. Each inclined narrow pattern seen in Figure 4 represents a dense region orbiting circularly around the galactic center. The trajectory can be followed between the two spirals; i.e., for about 1/4–1/2 of the galactic rotation. This means that the substructures, i.e., spurs, in the interarm regions are linked with the nonsteady “chaotic arms.” Contrary to the classic galactic shock solution, the chaotic arms found here are located downstream of the potential trough on average, which suggests that the ISM does not behave like a smooth fluid. Typically, the width of the waves is \( \Delta \phi \approx \pi/6 \). Apparently the quasi-stable structures found here are no longer “shocks” in a hydrodynamic sense.

Finally, the positions of “massive star” particles overlaid on a density map at \( t = 155 \) Myr are shown in Figure 5. It is clear that massive stars form clusters, most of which are distributed near the potential trough, mostly downstream, and they form spiral features. This is reasonable, since the stars originate in cold, dense clouds. In real galaxies, the massive star complexes should form H\( \, \text{ii} \) regions around them, and they illuminate the spiral structures. Our results show that the H\( \, \text{ii} \) regions are offset to the downstream of the dust spirals, which is consistent with

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\(^4\) The isodensity map is a method to represent a 3D density field by a opaque surface on which the volume density is the same.
observations (del Rio & Cepa 1998; Gittins & Clarke 2004). However, as can be seen in Figure 6, the spiral arms are not uniform, and the positions of density peaks in the pseudo-arms are not uniquely defined. Therefore, it would be difficult to derive dynamical information such as the pattern speed of the spiral potential and the position of corotation from observational data; for example, the offset between the B-band and I-band arms, or that between the dust arms and the Hα arms (del Rio & Cepa 1998; Gittins & Clarke 2004).

4. DISCUSSION

4.1. Effect of the Pattern Speed of the Potential
The density structure of the ISM in a spiral potential can be affected by two free parameters here: the pattern speed and the strength of the spiral potential. As mentioned in § 1, bifurcation features of spiral arms could be explained by Lindblad and ultraharmonic resonances (Shu et al. 1973; Chakrabarti et al. 2003). This substructure of the spiral shocks (i.e., “branches”) is also seen in some models by Shetty & Ostriker (2006), but we do not see clear evidence of the resonant structures in our results regardless of the presence of resonances. Figure 6c shows the density distribution at \( t = 61 \) Myr of a model with a pattern speed of \( \Omega_p = 60 \text{ km s}^{-1} \text{ kpc}^{-1} \). As in the fiducial model (Fig. 6b), in which \( \Omega_p = 30 \text{ km s}^{-1} \text{ kpc}^{-1} \), the density field is characterized by inhomogeneous spiral arms and spurs in the interarm regions. This is also the case in a model with \( \Omega_p = 15 \text{ km s}^{-1} \text{ kpc}^{-1} \) (there are no resonances in the disk, except for an ILR at \( R = 0.05 \) kpc). In Figure 6a, the strength of the bar is half (i.e., \( \epsilon_0 = 0.05 \)) of the fiducial model (Fig. 6b) with the same pattern speed. As in the fiducial model, the complicated spiral arms are formed, but they are located further downstream than they are in the model with a stronger spiral potential at this moment.

The average location of the spiral arms is probably affected by the relative velocity of the gas to the spiral potential and the depth of the potential. For a smaller relative velocity (i.e., a larger value of \( \Omega_p \)) and/or a deeper potential, the gas clouds tend to be trapped near the potential minimum. On the other hand, for smaller pattern speeds and/or a shallower potential, the clouds pass the potential minimum and decelerate. As a result, density peaks tend to be formed further downstream on average.

4.2. Toward Increasingly Realistic Models
In the present model, we assume a time-independent two-arm spiral potential with a constant pitch angle, for which the resultant morphology of the gas is quite complicated and time-dependent. These features are qualitatively consistent with near-infrared and optical observations of various types of spiral galaxies (Seigar & James 1998; Grosbol & Patsis 1998). In spite of the flocculent appearance of dust and young stars, the old populations seen in the K band are dominated by two-arm spirals. The pitch angles of the K-band arms are distributed between \( 5^\circ \) and \( 10^\circ \), independent of the galaxy’s Hubble type (Seigar & James 1998). The phase offset between the potential minimum, the locations of young stars, and the locations of dust arms in the real galaxies could be used to study the physical origin of the spiral arms. Unfortunately, observational constraints on the offset of the spiral arms from different components are ambiguous (del Rio & Cepa 1998), partly because the stellar and gaseous arms are not smooth, and partly because it is hard to trace their positions, as is the case in our simulations. The distributions of the gas and massive stars are far from regular, but they are more complicated than the predictions of previous idealized models.

For increasingly realistic models, one should take into account the nonlinear gravitational coupling between the ISM and the stellar potentials, as well as a realistic treatment of the ISM itself. This should be achieved in self-consistent, cosmological simulations of the formation of spiral galaxies. One should realize, however, that even in recent simulations (e.g., Springel & Hernquist 2005; Governato et al. 2007), the mass and spatial resolutions for gas are \( 10^3-10^6 \text{ M}_\odot \) and subkiloparsec, and therefore it is hard to represent the complicated multiphase structures of the ISM in spiral galaxies as seen in the present simulations.
A much higher numerical resolution is also essential to be able to resolve the density waves in a stellar disk.

It is not clear how magnetic fields affect the stability of the multiphase ISM in a spiral potential. We would like to consider this problem in future 3D MHD simulations in which realistic cooling and heating processes, as well as the self-gravity of the gas, are at least considered.

5. CONCLUSIONS

High-resolution hydrodynamic simulations that take into account both the self-gravity of the gas and realistic cooling and heating processes for the ISM reveal for the first time that the galactic spiral arms of the ISM are neither hydrodynamic shock waves nor an assembly of long-lived, bullet-like cloudlets. The global spiral arms consist of complicated time-dependent substructures from which stars can be formed, but over a long time (at least 5–6 rotational periods), they exist in stable forms under the influence of the spiral potential. The pseudospiral in the multiphase ISM is robust for energy input from supernovae, which mainly affects the vertical nonuniform structure of cold and hot gases. The pattern speed of the spiral potential and its strength are not key parameters to alter the above features.

The ISM in galactic disks has often been represented by an isothermal, non–self-gravitating fluid or inelastic particles in many astrophysical simulations. Moreover, introducing a periodic boundary condition and reducing spatial dimensions were common practices. However, those kinds of simplifications do not necessarily represent the nature of spiral galaxies. Magnetic fields are not considered in the present simulations, but the present results suggest that even if the magnetic fields are weak, the spiral patterns can exist in a steady state on a global scale. The effects of magnetic fields and other important physical processes, such as UV radiation and chemistry, should be investigated and should be based on 3D global models, as presented in this paper.

The present treatment of the multiphase ISM could be used for direct comparison with observations, coupled with radiative transfer calculations for various observational probes (e.g., Wada et al. 2000; Wada & Tomisaka 2005). Fine structures of molecular gas associated with the spiral arms and in the interarm regions in external galaxies, which could be compared with the present numerical model, will be revealed by high-resolution observations; e.g., by the Atacama Large Millimeter/Submillimeter Array.

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