FORMATION OF CAVITIES, FILAMENTS, AND CLUMPS BY THE NONLINEAR DEVELOPMENT OF THERMAL AND GRAVITATIONAL INSTABILITIES IN THE INTERSTELLAR MEDIUM UNDER STELLAR FEEDBACK

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ABSTRACT

Based on our high-resolution two-dimensional hydrodynamical simulations, we propose that large cavities may be formed by the nonlinear development of the combined thermal and gravitational instabilities, without need for stellar energy injection in a galaxy modeling the Large Magellanic Cloud (LMC). Our numerical model of star formation allows us to follow the evolution of the blast waves due to supernovae in the inhomogenous, multiphase, and turbulent-like media self-consistently. Formation of kiloparsec-scale inhomogeneity, such as cavities as seen in the observed H I map of the LMC, is suppressed by frequent supernovae (the average supernova rate for the whole disk is \( \sim 0.001 \text{ yr}^{-1} \)). However, the supernova explosions are necessary for the hot component (\( T_v > 10^6 - 10^7 \text{ K} \)). Position-velocity maps show that kiloparsec-scale shells/arcs formed through nonlinear evolution in a model without stellar energy feedback have kinematics similar to explosive phenomena, such as supernovae. We also find that dense clumps and filamentary structure are formed as a natural consequence of the nonlinear evolution of the multiphase interstellar medium (ISM). Although the ISM on a small scale looks turbulent-like and transient, the global structure of the ISM is quasi-stable. In the quasi-stable phase, the volume filling factor of the hot, warm, and cold components are \( \sim 0.2, \sim 0.6, \) and \( \sim 0.2 \), respectively. We compare observations of H I and molecular gas of the LMC with the numerically obtained H I and CO brightness temperature distributions. The morphology and statistical properties of the numerical H I and CO maps are discussed. We find that the cloud mass spectra of our models represent a power-law shape, but their slopes change between models with and without the stellar energy injection. We also find that the slope depends on the threshold brightness temperature of CO.

Subject headings: galaxies: individual (Large Magellanic Cloud) — galaxies: structure — ISM: kinematics and dynamics — ISM: structure — methods: numerical

1. INTRODUCTION

The topology of the neutral interstellar medium (ISM) can be studied in great detail by the spatial and velocity structures in the neutral H I gas. A recent high-resolution H I survey of the Large Magellanic Cloud (LMC) reveals that the structure of the neutral atomic interstellar gas is dominated by numerous holes and shells as well as complex filamentary structure (Kim et al. 1998). These features are commonly seen in recent high-resolution H I images of nearby galaxies obtained with radio synthesis interferometers (Deul & den Hartog 1990; Puche et al. 1992; Staveley-Smith et al. 1997; Walter & Brinks 1999; Stanimirovic et al. 1999). In general, the shell-like and hole structure seen in H I has been understood as the cumulative effect of stellar winds from massive stars and supernova explosions evacuating the cool ISM (Tenorio-Tagle 1988; van der Hulst 1996; Oey 1996; Oey & Clarke 1997). However, the extensive study of H I shells in the LMC shows that there is a relatively weak correlation between the H I shells and the ionized gas traced by the H \( \alpha \) regions and H II filaments (Kim et al. 1999). Furthermore, the correlation between the H I shells and 122 OB stellar associations in the LMC is not very tight (Kim 1999). Rhode et al. (1999) claimed that there are no remnant star clusters at the center of the H I holes in Holmberg II and that it is inconsistent with the supernova hypothesis. Moreover, the energy source generating the kiloparsec-scale supergiant H I holes is a puzzle. These issues raise an interesting question about whether or not H I shells/holes have been formed by the interaction between stars and the ISM.

Recent hydrodynamical simulations by Wada & Norman (1999) demonstrate that a gravitationally and thermally unstable disk, which models an ISM in galaxies, can generate the cold, dense clumps and filaments surrounded by a hot, diffuse medium. They show that porous structure is a natural consequence of the nonlinear evolution of the ISM. This result strongly suggests that some fraction of H I shells, supershells, or holes seen in galaxies does not relate to the interaction between stellar activities and the ISM.

The other important component of the ISM is the molecular gas. Molecular clouds are potential sites of star formation, but their formation mechanism and the relationship between their evolution and star formation have been poorly understood. Dense molecular hydrogen is traced by the rotational transition of CO, and a recent high-resolution survey of \( ^{12}\text{CO} \) (\( J = 1-0 \)) in the LMC with NANTEN, which is a 4 m millimeter-wave telescope at Las Campanas Observatory, established a comprehensive view of the giant molecular clouds (GMCs) in the LMC (Fukui et al. 1999). Since the gas clumps, whose size is typically 10–100 pc, in the simulations by Wada & Norman (1999) are dense (\( n > 1000 \text{ cm}^{-3} \)) and cold (\( T = 10–100 \text{ K} \)), they are counterparts of the observed GMCs in the LMC or other galaxies.

Using numerical simulations, Feitzinger et al. (1981) and Gardiner, Turfus, & Putman (1998) have studied global

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dynamics of the ISM and star formation in the LMC. Although the numerical methods they used are different, the stochastic self-propagating star formation model (e.g., Seiden & Gerola 1982) in Feitzinger et al. (1981) and the sticky particle method in Gardiner et al. (1998) are both phenomenological concerning the structure and dynamics of the ISM and star formation processes. Unfortunately, the spatial resolution (100 pc in Feitzinger et al. 1981) and mass resolution (6 × 10^4 M_☉), which corresponds to ~200 pc for n ~ 1 cm⁻³ and H ~ 100 pc, in Gardiner et al. (1998) in these simulations are not good enough for comparison between the models and recent high-resolution observations (~15 pc for H i: Kim et al. 1998; ~40 pc for CO (J = 1–0): Fukui et al. 1999).

In this paper, we apply the numerical scheme used in Wada & Norman (1999) to an LMC-type model galaxy, and we conduct two-dimensional hydrodynamical simulations of the multiphase ISM in an LMC-like model galaxy, taking into account self-gravity of the gas, radiative cooling, and various heating processes, such as supernova explosions. High spatial resolution (7.8 pc) and a modern hydrodynamical scheme allow us to model the star formation and its feedback less phenomenologically, and therefore our approach requires fewer assumptions than previous semi-analytical and numerical approaches (e.g., a review by Shore & Ferrini 1995). In contrast to the model used in Wada & Norman (1999), the rotation curve assumed here is nearly rigid, as suggested in the LMC or other LMC-type dwarf galaxies. We derive the H i and CO brightness maps from the simulations. Then we compare these simulation results with the H i and CO observations of the LMC.

In § 2, we describe our numerical method and models. In § 3, the numerical results, with and without star formation, of the morphology and statistical structure of the ISM are discussed and then compared with the observations. Position-velocity (PV) diagrams derived from the numerical results are also discussed. Comparison with past numerical simulations and other implications are discussed in § 4, and conclusions are presented in § 5.

2. NUMERICAL METHOD AND MODELS

Taking into account the multiphase and inhomogenous nature of the ISM is crucial for realistic simulations of global star formation in galaxies. Stars are formed preferentially in cold molecular gas, and supernovae produce low-density, high-temperature gas. Interaction between such different phases are also important (e.g., McKee & Ostriker 1977; Ikeuchi, Habe, & Tanaka 1984). In order to simulate dynamics of the inhomogenous, multiphase interstellar matter and star formation, our numerical method has the following features. (1) We use high spatial resolution (7.8 pc) for diffuse gas to high-density gas, and use a Euler mesh code with 1024² Cartesian grid points. (2) The simulations are global in order to study the effects of galactic rotation and other kiloparsec-scale phenomena to the local structure of the ISM. (3) Self-gravity of the gas is calculated. (4) Radiative cooling for gas whose temperature is between 10 and 10^8 K is taken into account. (5) Various heating processes are included. Here we assume photoelectric heating due to dust grains and UV radiation, supernova explosions, and stellar wind from massive stars. (6) High numerical accuracy for shocks is achieved with a modern hydrodynamical scheme. This is crucial, because the ISM is usually supersonic and supernovae produce strong shocks.

We solve the following hydrodynamical equations and the Poisson equation numerically in two dimensions to simulate the evolution of a rotating gas disk in a stellar potential:

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

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

\[
\frac{\partial E}{\partial t} + \frac{1}{\rho} \nabla \cdot [(p E + p) \mathbf{v}] = \Gamma_{\text{UV}} + \Gamma_{\text{SG}} - \rho \Lambda(T) ,
\]

\[
\nabla^2 \Phi_{\text{sg}} = 4\pi G \rho ,
\]

where \(\rho, p, v\) are the density, pressure, and velocity of the gas, and the specific total energy \(E \equiv |\mathbf{v}|^2/2 + p/(\gamma - 1) \rho\), with \(\gamma = 1.4\). We assume a time-independent external potential \(\Phi_{\text{ext}} \propto v_z^2/(R^2 + a^2)^{1/2}\), where \(a = 2.5\) kpc is a core radius of the potential and \(v_z = 63\) km s⁻¹ is the maximum rotational velocity, mimicking the rotation curve of the LMC (Kim et al. 1998). Since the total gas mass is about 10% of the total dynamical mass (see below), the effect of self-gravity of the gas on the rotation curve is not significant. In fact, the rotation curve after the system evolves is close to the rigid rotation (see § 3.3 and the PV diagrams in Fig. 10).

We also assume a cooling function \(\Lambda(T)\) (10 < \(T_\text{cool}\) < 10⁸ K; Spaans & Norman 1997). The cooling processes taken into account are (1) recombination of H, He, C, O, N, Si, and Fe, (2) collisional excitation of H i, C i–iv, and O i–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. As a heating source, \(\Gamma_{\text{UV}}\), we assume a uniform UV radiation field (Gerritsen & Icke 1997), which is normalized to the local interstellar value, and photoelectric heating by grains and polycyclic aromatic hydrocarbons. The bulk of the heating for the 10²–10⁴ K gas is provided by photoemission of UV-irradiated dust grains (Bakes & Tielens 1994).

We consider two feedback effects of massive stars on the gasdynamics, namely, stellar winds and supernova explosions, although our results show that the former is less effective than the latter. We first identify cells that satisfy criteria for star formation. The criteria are a surface density threshold (\(\Sigma_{\text{crit}} > \Sigma_s\)) and a critical temperature (\(T_{\text{crit}} > T_s\)) below which star formation is allowed. The surface density is defined as \(\Sigma_{\text{crit}} = 2H\rho\), where \(H\) is the scale height and assumed to be constant (100 pc). In these simulations we take \(\Sigma_s = 40 M_\odot\) pc⁻² and \(T_s = 15\) K (model Star Formation 1, hereafter SF1) and 10 times larger threshold density, \(\Sigma_s = 400 M_\odot\) pc⁻² and \(T_s = 15\) K (model SF2). These criteria are chosen to satisfy the condition \(L_\gamma < 0.1\Delta\) or \(L_\gamma < 0.01\Delta\), where \(L_\gamma\) and \(\Delta\) are the Jeans length and the size of each cell. The volume filling factors of the star-forming cells to the total volume are typically ~5 × 10⁻³ and ~5 × 10⁻⁴ for models SF1 and SF2, respectively; the star-forming sites are cold, clumpy regions. We also assume the star-forming criteria must last 10⁵ yr for each cell before the star formation is initiated. Since the spatial resolution is fine enough in relation to the GMC size, we do not have to assume any global criteria for gravitational instability to identify star-forming sites. Assuming the Salpeter initial mass function (IMF) with \(m_u = 120 M_\odot\) and \(m_l = 0.2 M_\odot\),
we create test particles representing massive stars ($\geq 8 M_\odot$) in the star-forming cell. The kinematics of the test particles in the external potential and the self-gravity potential of the gas are traced by the second-order time-integration method. The stars (test particles) inject energy due to stellar winds during their lifetime, which is approximately $\sim 10^7$ yr (Leitherer, Robert, & Drissen 1992). When one of stars represented by a test particle explodes as supernova, an energy of $10^{51}$ ergs is injected into the cell as thermal energy where the test particle is located at that moment. The cooling procedure is not used for such cells, but the cells adjoining the supernova cell are treated normally. Evolution of the supernova remnant (SNR) is very dependent on its environment. In contrast to past numerical studies of the ISM with supernova explosions on a galaxy scale, we do not introduce simple evolutionary models for the SNR, such as the Sedov solution and heating efficiency for the ISM due to a supernova. With our code, two-dimensional evolution of blast waves caused by supernovae in an inhomogeneous and turbulent medium with global rotation is simulated explicitly. Therefore, we can trace consistently the thermal and dynamical evolution of the ISM around the star-forming regions and the associated SNRs and superbubbles (see also Norman & Ikeuchi 1989).

The hydrodynamic part of the basic equations is solved by the third-order advection upstream splitting method (AUSM; Liou & Steffen 1993). After testing this code for various hydrodynamical one- and two-dimensional problems, we find that AUSM is as powerful a scheme for astrophysical problems as are the piecewise parabolic method (Woodward & Colella 1984) and ZEUS (Stone & Norman 1992) codes. More details about our numerical code and test results are described in Wada & Norman (2000).

We use $1024^2$ Cartesian grid points covering an $8 \times 8$ kpc$^2$ region. The spatial resolution is 7.8 pc. A periodic Green function is used to calculate the self-gravity for the $8 \times 8$ kpc$^2$ region with 2048$^2$ grid points (Hockney & Eastwood 1981). The second-order leap-frog method is used for the time integration. We adopt implicit time integration for the cooling term in equation (3).

The initial disk is axisymmetric and rotationally supported ($R = 3.7$ kpc) with uniform surface density, $\Sigma_g = 12 M_\odot$ pc$^{-2}$, and the total gas mass is $5 \times 10^8 M_\odot$ (Kim et al. 1998). Random density and temperature fluctuations are added to the initial disk. Amplitude of the initial fluctuations is less than 5% of the unperturbed values and has an approximately white noise distribution. The initial temperature is set to $10^4$ K ($R \leq 3.7$ kpc) and $10^2$ K ($R > 3.7$ kpc). The reason why we chose the low temperature in the outer region is to avoid the numerical artifact of the boundaries, i.e., reflection and generation of waves or shocks, for the initial evolution of the gas disk. In ghost zones at the boundaries of the calculating region (i.e., $8 \times 8$ kpc$^2$), all physical quantities remain at their initial values during the calculations. From test runs we found that this boundary condition is much better than “outflow” boundaries, because the latter cause strong unphysical reflection of waves at the boundaries.

3. RESULTS

3.1. Evolution and Structure of the ISM

3.1.1. Model without Star Formation

Figure 1 shows the time evolution of density and temperature of a model without star formation and energy feedback (hereafter we call this model NSF). As a result of gravitational and thermal instability in the gas disk, clumpy fluc-
turbulent ISM models (Bania & Lyon 1980; Chiang & Bregman 1988; Rosen & Bregman 1995; Vázquez-Semadeni, Passot, & Pouquet 1995; Passot, Vázquez-Semadeni, & Pouquet 1995; Gazol-Patino & Passot 1999). Clump mass is increasing during the initial linear and nonlinear evolutionary phase (\(t < 200 \text{ Myr}\)) because of mass accretion and merging with other clumps or filaments, but in the quasi-stationary phase, disruption processes of the clumps, such as the local tidal field (e.g., interaction between clumps or shear) or shocks, prevent monotonic increase of the mass of each clump. Since we introduce the cutoff temperature for the cooling (i.e., 10 K), the gaseous pressure prevents the dense clouds from further collapsing toward singularities. The angular momentum also supports the clouds (see §3.3).

The density and temperature structures (Fig. 1) are similar to those in the model of Wada & Norman (1999), where a smaller disk is investigated (the radius is 1 kpc), but the present model shows kiloparsec-scale inhomogeneity and a more asymmetric distribution against the galactic center. This difference is probably caused by the different rotation curves used in the two models: rigid rotation versus differential rotation. With a rigid rotation, random and turbulent motion dominates the circular rotation in the central region. With the global shear, on the other hand, global spirals develop toward the galactic center.

### 3.1.2. Models with Star Formation

Figure 3 represents density and temperature maps of the model SF2 at \(t = 833 \text{ Myr}\). The model SF1, which has a 10 times smaller threshold density for the star formation criterion (see §2), shows very similar density morphology and temperature structure. The red regions in the temperature map are hot gaseous regions where \(T_g > 10^4 \text{ K}\). They are young (<10^6 yr) SNRs. Figure 3 also shows that most young SNRs are not axisymmetric. This is because the background ISM is highly inhomogeneous and the radiative cooling at the dense filaments is so effective that it prevents the blast waves from expanding axisymmetrically. Typical size of the hot cavities is less than 500 pc. Some bubbles together form kiloparsec-scale superbubbles. The hot region around \((-3,-1)\) is one example. Note that the size of the cavities is expected to change away from the galactic plane in a three-dimensional model (see also §4).

Although the filamentary and clumpy structures of the gas that result in the star-forming models are similar to those of model NSF, the kiloparsec-scale inhomogeneity seen in model NSF (Fig. 1) is not apparent in the SF models. The large-scale inhomogeneity in the models SF1 and SF2 is less prominent than that of model NSF. This is because the timescale for making the kiloparsec-scale holes, which is a dynamical timescale, \(\sim 10^8 \text{ yr}\), is much longer than the timescale for supernova explosions and evolution of the blast waves, \(\lesssim 10^6 \text{ yr}\). Approximately 10^3 supernovae kpc^{-2} explode in this model during \(\sim 10^8 \text{ yr}\). The kiloparsec-scale low-density cavities, which are formed as a result of evacuation of gas due to gravitational and thermal instabilities, cannot evolve under such frequent supernova explosions.

We find that the supernova rate fluctuates in a timescale \(\sim 10^7 \text{ yr}\), but it stays in the range \((4-10) \times 10^{-4} \text{ yr}^{-1}\) during \(6 \times 10^{16} \text{ yr}\) in model SF2 (Fig. 4). This behavior also appears in model SF1, but the supernova rate becomes smaller for the larger threshold density \([\sim (8-12) \times 10^{-4} \text{ yr}^{-1}]\). ROSAT observed 46 SNRs and more candidates in
the LMC (Haberl & Pietsch 1999). If we assume the ages of SNRs are between \( \sim 10,000 \) and \( \sim 30,000 \) yr, then we have a supernova explosion every 250 or 750 yr. This indicates a supernova rate in the LMC of about 0.0013 or 0.004 yr\(^{-1}\). If we use the larger threshold density for the star formation in our model than that in model SF2, this results in a supernova rate smaller than \( \sim 0.001 \) yr\(^{-1}\). Therefore, a threshold density much larger than 400 M\(_{\odot}\) pc\(^{-2}\) would be excluded for modeling the LMC if we assume that the star formation efficiency is 10% or less and the standard IMF.

In Figure 5, the star particles at \( t = 245 \) Myr in model SF1 are plotted, and one may compare the plot to the density distribution (right panel) of the same snapshot. Massive stars are not uniformly distributed, but they form clusters ("OB associations"). It is notable that the distribution of the star clusters does not necessarily correlate with the inhomogenous gaseous structure. In other words, cavities are not necessarily associated with the OB associations. This is also seen in simulations by other groups, for example, dimensional simulations of a highly compressible isobaric, non-self-gravitational fluid with star formation (Scalo & Chappell 1999).

### 3.2. Line Emission Maps and Comparison with the Observations

With numerical simulations, we have density, temperature, and velocity fields (spatial resolution is 7.8 pc). Using this information, we compute an H\(_{\text{I}}\) 21 cm brightness map and a CO (\( J = 1-0 \)) line map for models NSF, SF1, and SF2. These maps can be directly compared with the
recent high-resolution surveys of the LMC: H I with Australia Telescope Compact Array (ATCA; Kim et al. 1998) and CO ($J = 1–0$) with NANTEN (Fukui et al. 1999).

With the numerical results described above, the following procedure is followed to compute an H I 21 cm brightness map. It is assumed that atomic hydrogen is in mostly neutral form in those regions where the temperature is at least a factor of 2 less than 8000 K, a value typical of (mostly ionized) H II regions and motivated by measurements of the kinetic temperatures of H I clouds and H I intercloud gas. It is also assumed that the H I level populations of interest follow a thermal distribution in those regions along the line of sight and that this mostly neutral gas dominates the integrated emissivity. The line of sight is face-on, i.e., perpendicular to the grid used for the hydrodynamic simulations. The two-dimensional density is used as a column density in the radiative transfer calculations, which are done in three dimensions by assuming a scale height for the neutral gas of $H = 100$ pc, thus converting the column density in a (constant) local density for each point along the line of sight. It is this three-dimensional grid, with two-dimensional hydrodynamic information, that is used to determine the H I central brightness temperature in the Monte Carlo procedure (Spaans 1996), where the ambient radiation field and its interactions with matter are represented by a discrete number of “photon packages.” This method is three-dimensional and explicitly includes optical depth effects as well as the detailed velocity field of the hydrodynamical simulations for photons that travel along lines of sight that are not face-on. These latter photon trajectories need to be incorporated when the level populations are not in thermal equilibrium, i.e., for CO. A local velocity dispersion $\Delta V$ of $1.29 \times 10^{4} T^{1/2}$ cm s$^{-1}$ is adopted for a kinetic temperature $T$, with a minimum of 0.5 km s$^{-1}$ due to micro turbulent motions. For each grid point in the hydrodynamical simulation, the Monte Carlo radiative transfer then yields the integrated H I 21 cm intensity along the line of sight.

For the CO ($J = 1–0$) line the approach is similar to the H I case, with the appropriate correction factor in $\Delta V$ for the different atomic weight of the CO molecule. Furthermore, a carbon chemistry is added to compute the abundance of CO (Spaans & van Dishoeck 1997) for a dust abundance equal to one-fifth of solar. This chemistry is well understood (van Dishoeck & Black 1988), and care has been taken to include, for each computed line of sight and corresponding column density, the important self-shielding transitions of H$_2$ and CO (see Spaans et al. 1994). The ambient average interstellar radiation field, required for the ambient chemical balance, is determined by scaling with the LMC B-band surface brightness in magnitudes per square arcsecond with respect to Galactic. This typically yields an enhancement of a factor of 3–5 in the mean LMC energy density compared to Galactic. It is assumed, because the hydrodynamical simulations are two-dimensional, that to compute the local CO emissivity and the ambient chemical equilibrium, the gas density is given by the particular line-of-sight column density divided by a scale height of $H = 100$ pc for the neutral gas. The scale height does not strongly influence the qualitative features in the presented maps.

Figure 6 presents H I 21 cm and CO ($J = 1–0$) line brightness temperature maps calculated from the numerical data of model NSF at $t = 800$ Myr, using the procedure described above. Figure 7 is the same plot as Figure 6, but for model SF2 at $t = 834$ Myr. The size of the H I filaments, shells, and holes in model NSF is $\sim 1$ kpc. The filaments and cavities in the outer region ($R > 2$ kpc) of model SF2 are also kiloparsec-scale. We would like to emphasize that large cavities ($> 1$ kpc) and filaments in model NSF are not caused by a direct dynamical effect of star-forming activities but by the nonlinear development of gravitational and thermal instabilities.

The CO emission is localized in many clumps (size $\sim 10$–100 pc) or cloud complexes (size $\sim 0.1$–1 kpc) in model NSF. Such CO “cloud” complexes could be sites for active star-forming regions, such as 30 Dor in the LMC. Model SF2 shows a more uniform distribution of “stars” than in model NSF.

Figures 8a and 8b show mass spectra of molecular clouds obtained from the CO brightness temperature ($T_B$) distribution of models NSF and SF2. We identify clouds and their
Fig. 6.—Brightness temperature $T_B$ (K) maps of $\text{H} \, \text{I}$ (left) and CO ($J = 1-0$) (right) computed from data of model NSF at $t = 800$ Myr. The intensity of $\text{H} \, \text{I}$ is log-scaled.

Fig. 7.—Same as Fig. 6, but for model SF2 at $t = 834$ Myr

Fig. 8.—(a) Mass spectrum of CO clouds for model NSF for three thresholds of the brightness temperature, $T_B = 30$ K (solid line), 50 K (dashed line), and 100 K (dotted line). The thick line shows $dN_M/dM \propto M^{-1.7}$, (b) Same as (a), but for model SF2.
mass by the following procedure. Assuming a threshold $T_B$ for the CO map (Figs. 6 and 7), we have many islands of CO emission. Most islands are not round in shape, but are elongated or have a filament-like shape. We derive the mass of the islands using the surface density of the simulation data. Therefore, the mass in Figure 8 is the total gas mass of each island, not the virial mass. Here we plot three histograms for three different thresholds. The mass spectrum for model NSF shows a power law, which is roughly $dN_c/dM_v \propto M_v^{-1.7}$, where $dN_c$ is number of clouds between the mass $M_v$ and $M_v + dM_v$, but this slope does not significantly depend on the threshold brightness. On the other hand, the spectrum of the star-forming model is steeper than the model without the energy feedback, especially for a small threshold: $dN_c/dM_v \propto M_v^{-1.7}$, $M_v^{-2.3}$, and $M_v^{-2.7}$ for model SF2 with $T_B = 100, 50$, and $30$ K, respectively. The behavior of the slope to the threshold $T_B$ in models NSF and SF2 indicates that the stellar energy feedback changes the structure of the low-density envelope of the dense clumps.

The NANTEN survey discovered about 100 molecular clouds in the LMC, and their mass spectrum is $dN/dM_v \propto M_v^{-1.5+0.1}$ for a range $10^3-10^6 M_\odot$ (Fukui et al. 1999), where $M_v$ is the virial mass of the cloud estimated by using the observed line width. In our model, smaller clouds ($M_v < 10^5 M_\odot$) tend to have smaller mass compared to their virial mass estimated from their internal velocity dispersions. In other words, the smaller clouds are not in equilibrium, but rather in a transient phase (Vázquez-Semadeni et al. 1995). We find a rather weak but positive correlation between the cloud mass $M_c$ and the virial mass $M_v^{1/2}$ in our model. The mass spectrum of the model SF2 would be $dN_c/dM_v \propto M_v^{-3.4}$ if we use the lowest threshold, $T_B = 30$ K. A similar discussion of the interpretation of the cloud mass spectra based on two-dimensional numerical simulations of the ISM has been given by Vázquez-Semadeni, Balleseros-Paredes, & Rodríguez (1997, hereafter VBR97; see § 4).

The maximal mass of the clouds is approximately $10^{6.5} M_\odot$ and $10^{5.5}-10^6 M_\odot$ in model NSF and models with star formation (SF1 and SF2). This implies that very massive clouds ($>10^6 M_\odot$) are difficult to grow under the frequent supernova explosions. The maximal masses of the observed molecular clouds are about $10^{4.5} M_\odot$ (Fukui et al. 1999), which seems to prefer model NSF. However, this does not mean that the star formation and its energy feedback are not important for shaping the ISM in the LMC, but it does imply that the largest clouds could evolve preferentially in an environment where supernovae are not frequent. However, one should be careful when making comparisons between the observed and numerical mass spectra, because the definition and identification of the "cloud" are not exactly identical and are related to noise level in observations.

We also find that the H I map of the computational model shows similar statistical properties to the observed H I map. Figure 9 shows the H I luminosity function, i.e., the histogram of the observed and numerical H I map of the LMC. The H I brightness temperature has been computed from $T_B = S_\nu/2k_\nu\Omega_{ab}$; $S_\nu$ is the H I flux density, $k_\nu$ is Boltzmann’s constant, and $\Omega_{ab}$ is the solid angle of the synthesized beam of ATCA mosaicked map. The H I intensity is determined from the integral of the brightness temperatures $\int T_B dv$ over the peak H I line profile, where $dv$ is the channel width in kilometers per second. The H I luminosity functions appear to have lognormal distribution for both the observed values and for model NSF. The distributions of the H I luminosity function of the models NSF and SF2 for lower surface brightness ($T_B < 1000$ K) are similar to the observed one. The model SF2, on the other hand, shows excess above $T_B > 1000$ K compared to the observations. These high-brightness regions originate from shock-compressed, dense gas.

### 3.3. Position-Velocity Diagrams

PV diagrams give us information on the kinematics of the ISM. In Figure 10a, we show the PV diagram in which the $y$-component of velocity ($v_y$) is integrated through $x$-positions for the gas $\Sigma_g < 10^2 M_\odot$ pc$^{-2}$ in model NSF. Many arclike structures in Figure 10a look like expanding shells originating from explosive phenomena in the ISM. However, they are not caused by explosions, because there is no energy input due to supernovae in model NSF. The arcs in the PV diagram are actually caused by the gases that form filament-like structures seen in the density map (Fig. 1). The filaments and shells exhibit noncircular motion of the order of 10 km s$^{-1}$, and their shape continuously changes. Here we would like to emphasize that it is hard to distinguish, on the PV diagrams, between expanding shells and such shell-like structures that are changing in shape as a result of local random motion.

From Figure 10b, which is the same as Figure 10a but for $\Sigma_g > 10^2 M_\odot$ pc$^{-2}$, we see the dense and compact clumps rotating ~10–30 km s$^{-1}$, which are shown as steep dotted lines on the PV diagram. Here we can identify about 80 clumps, and about half of them show retrograde rotation against the sense of galactic rotation. A representative clump can be seen at $(x_c, v_y) = (-0.5, -50)$, and a less prominent one is at $(1.5, 25)$ and $(3, 75)$. Rotation of the clouds is important for internal structure, motion, and star formation in the molecular clouds. Unfortunately, the spatial resolution in the NANTEN survey (~40 pc) is insufficient to resolve the rotation of each molecular cloud of the LMC. High-resolution observations and statistical analysis...
of kinematics of molecular clouds in external galaxies are necessary to understand the formation of molecular clouds and star formation processes.

Figure 10c shows the similar features shown in Figure 10a, but for model SF1 at $t = 610$ Myr. Arclike structures seen in the PV map for model NSF are not clearly shown in this map. This means that the line-of-sight velocity field is much more random and chaotic than the NSF model, and there is no prominent large-scale coherent motion in the ISM in the model with stellar energy feedback.

4. DISCUSSION

The comparison of our model calculations with the observations of the LMC indicates that the star formation models are more consistent with the formation of small ($\ll 1$ kpc) and hot bubbles ($T \gtrsim 10^7$ K), which have been detected by X-ray diffuse emission. The power-law slope of the cloud mass spectrum of the models is close to that of the observed one. On the other hand, the model calculations without the stellar feedback show even better agreement with global inhomogeneity of the H I and CO gas in the LMC, and the H I distribution function is also well represented in model NSF. Therefore, it is most likely that energy feedback to the ISM from massive stars and supernova explosions are important processes for producing hot gas, but they do not necessarily dominate dynamics and formation processes for the large-scale inhomogeneity observed in H I and CO gas in the LMC. However, one should note that the initial condition of the models (i.e., axisymmetric and uniform density distributions) causes nearly uniform star formations in the whole disk. If we begin the simulations from a more inhomogeneous disk, stars will be formed nonuniformly and effects of the stellar feedback will be different, depending on the location of the disk. We suspect that the more realistic model of the ISM in the LMC-type galaxy would be between our two extreme cases, but that model cannot be achieved by changing the threshold density of the star-forming model.
In our models with stellar feedback, typical sizes of the hot cavities are less than 500 pc. Some superbubbles can be formed in a outer disk region, and their linear sizes are $\sim 1$ kpc (see Fig. 3). Rosen & Bregman (1995) revealed in their two-dimensional, two-fluid (stars and gas) simulations in a disk galaxy that hot bubbles are formed by stellar activities and that their sizes depend on the energy injection rate. In their simulations, the linear size of the bubbles is up to $\sim 500-1000$ pc for the supernova rate 0.0075–0.03 yr$^{-1}$. This rate is 1–2 orders of magnitude larger than that of our star-forming models. Local, three-dimensional MHD simulations of the ISM with supernova explosions by Korpi et al. (1999) show that the linear size of the superbubbles is typically 200–400 pc, which is consistent with our SF models. Gazol-Patino & Passot (1999) compute the evolution of the ISM in a region of the Galactic plane of size 1 kpc$^2$ in a two-dimensional periodic domain. They found superbubbles due to about 3000 supernova explosions in $\sim 10^7$ yr, the largest one with a linear scale, $\sim 500$–1000 pc. The background density of their simulation is equivalent to that in the outer region of our simulations. The local (less than kiloparsec-scale) structure of the ISM of our global simulations, where hot bubbles and cold filaments coexist, is also similar to the local, two-dimensional simulations of the ISM with a periodic boundary condition (Vázquez-Semadeni et al. 1995). In conclusion, previous local models with supernova explosions in which superbubble formation is reported are consistent with our global models with stellar energy feedback concerning the size of the superbubbles.

The cloud mass spectra of models SF1 and SF2 are steeper than that of model NSF (Fig. 8). In other words, the stellar energy input affects the evolution of molecular clouds. VBR97 analyzed their two-dimensional hydro-magnetic simulations and showed that the mass spectra have the form $\frac{dN_c}{dM_c} \propto M_c^{-1.44 \pm 0.1}$ (cf. their Fig. 3 and our Fig. 8), and they reported that the mass spectra from observations are consistent with that from simulations in which the density field had been shaped by stellar activity. Note that for our mass spectrum of the star formation process, the slope is shallower for smaller clouds ($M_c < 10^3 M_\odot$) than that for massive clouds ($dN_c/dM \propto M^{-2}$). Therefore, our results might be consistent with the results of VBR97 (see also § 3.2). However, direct comparison between these two results is not straightforward, because there are a number of differences between our simulations and theirs in the numerical scheme (AUSM vs. pseudo spectral method), the boundary condition (global simulations vs. local periodic boundary), and the cooling curve, especially for $T_e < 100$ K ($\Lambda \neq 0$ vs. $\Lambda = 0$). The maximum density contrast is about 5000 in their model, but it is about $2 \times 10^5$ in our model. This difference is probably due to the different cooling curves for the cold gas and to the numerical scheme. In their numerical method, they added a mass diffusion term to the continuity equation in order to smooth out the density gradients (see also Vázquez-Semadeni et al. 1995). This could affect the structure of shocks and dense gas, i.e., the cloud mass spectrum. The recipe for the stellar energy feedback is also different. VBR97 assumed that once a star is formed, it remains fixed with respect to the numerical grid. In our models, the star particles orbit in the self-gravitational potential of the gas and the external fixed potential. The last point, however, would not be important if the number of stars is large enough or the ISM is fully turbulent. VBR97, on the other hand, include the magnetic field in their models. Therefore, again, one should be careful to make a direct comparison between results in the present paper and those in VBR97.

Our results imply that there are two mechanisms of cavity formation. One is the pure evacuation of gas from the low-density regions due to the gravitational and thermal instabilities; similar evacuation phenomena (Elmegreen 1994; Vázquez-Semadeni, Passot, & Pouquet 1996) are also observed in the simulations of the turbulent ISM without supernovae (Passot et al. 1995). The other is the formation of cavities due to supernovae and especially due to the synchronized explosions of stars in OB associations. The two processes are essential to produce the whole structure of the ISM. The latter is necessary for the hot ($T_e > 10^6$ K) component of the ISM. These two types of low-density regions are also observed in the two-dimensional, local simulations of the turbulent ISM with supernovae by Gazol-Patino & Passot (1999).

As mentioned in § 1, the origin of supergiant H II holes in galaxies has been controversial (see also Walter & Brinks 1999). If the observed kiloparsec-scale holes and shells are caused by explosive phenomena only, one needs highly energetic events such as gamma-ray bursts (Loeb & Perna 1998). However, our numerical simulations give an alternative explanation about the origin of the large-scale holes: the nonlinear evolution of the multiphase gas disk. In the multiphase ISM, most of the gas mass is concentrated in the cold, dense clumps and filaments, but the volume filling factor of such a component is much smaller than that of hot, diffuse gas. The hot regions are surrounded by dense filaments, as seen in Figures 1 and 3. Therefore, the multiphase ISM in a quasi-steady state is naturally porous. Our results suggest that if the energy feedback from massive stars is not effective, kiloparsec-scale inhomogeneity can be evolved in a disk in about several $10^8$ yr. Dense filaments are changing in shape as a result of the local random velocity field as well as the global shear and often show kinematics features similar to those of “expanding shells,” as seen in the PV map (§ 3.3). We suspect that many supergiant holes and shells in dwarf galaxies do not have an explosion origin but that supergiant shells far outside the disk plane cannot be formed without explosive events.

The work presented here yields the model for the ISM in an LMC-type galaxy. Nevertheless, there are couple of issues one should consider when constructing a complete numerical model of the LMC, including the interaction with the Small Magellanic Cloud, the optical bar, and the non-uniform UV radiation field due to active star-forming regions such as 30 Dor. Interactions with the Small Magellanic Cloud are important events for the star formation history in the LMC and the Magellanic Stream (Murai & Fujimoto 1980; Vallenari et al. 1996; Gardiner & Nobuchi 1996). The off-center optical bar could also perturb the global structure of the ISM and star formation in the LMC (Gardiner et al. 1998). However, the H I mapping (Kim et al. 1998) does not show clear evidence of the stellar bar, namely, offset shocks that are often seen in barred galaxies. It would be interesting to investigate the effect of the off-center stellar bar in our model. This might contribute to the formation of an active star-forming region such as 30 Dor.

In the present paper, we have not solved the vertical structure of the ISM. It is expected that the hot component behaves differently in three dimensions. The hot gas, which
is greater than $10^6$ K, cannot be confined in the disk plane (Rosen & Bregman 1995; Avillez 1999), and it would probably be blown out from the disk plane. The scale height of the hot gas should be larger than the cold gas, and as a result, the volume filling factor of the hot gas would be larger away from the disk plane. Thus, the radiative cooling would be less effective in the hot gas in three dimensions. This may affect interaction between cold and hot components and the feedback process on the ISM. For example, it is more difficult to form the supergiant holes with supernovae. In a subsequent paper, we will extend our method to three-dimensional modeling and investigate these problems.

5. CONCLUSIONS

Using high-resolution hydrodynamical simulations, we have computed the global dynamics and structure of the multiphase ISM in an LMC-type galaxy. As a result of gravitational and thermal instability in the gas disk, clumpy fluctuations evolve, and then the clumps merge and form filamentary structure in the nonlinear phase. Higher density clumps are formed in the filaments as a result of the gravitational instability or collisions between the filaments. Our numerical model of star formation allows us to provide the evolution of the blast waves due to supernovae explosions in the rotating, inhomogeneous, multiphase, and turbulent-like media. We find that the supernova rate in the model with stellar energy feedback is typically of the order of 0.001 yr$^{-1}$ during several hundred Myr but fluctuates rapidly (timescale $\sim$ 10 Myr) by a factor of 3 or 4. The model also shows that kiloparsec-scale low-density cavities seen in the observed H I map (Kim et al. 1998) are difficult to form with frequent supernovae, but supernovae are necessary to form hot bubbles where the gaseous temperature is greater than $10^6$ to $10^7$ K. Our result suggests that there are two possible causes of low-density regions in the ISM. The kiloparsec-scale inhomogeneity and arcs can be formed as a natural consequence of nonlinear evolution of the multiphase ISM in an LMC-type galaxy. We find in the PV diagram of the numerical models that filamentary structure in the non-stellar-forming model, which is caused by the gravitational instability, has kinematics similar to the structure formed by supernova explosions. The dense clouds are rotating, and about half of them show retrograde rotation against the sense of galactic rotation. Using the Monte Carlo radiative transfer code, we computed H I and CO brightness temperature distributions and compared them with those from the recent observations. The CO cloud mass spectrum in the model with stellar energy feedback is similar to the observed one (Fukui et al. 1999), but the H I distribution function is well fitted by the model without supernovae. Therefore, we conclude that the small-scale structure and dynamics of the ISM in the LMC is affected mainly by the stellar activities, but the gravitational instability significantly contributes to the global morphology and dynamics of the interstellar matter on a kiloparsec scale.

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