Global Evolution of a Self-Gravitating Multi-Phase ISM in the Central Kpc region of Galaxies

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Using high resolution, two-dimensional hydrodynamical simulations, we investigate the evolution of a self-gravitating multi-phase interstellar medium in the central kiloparsec region of a galactic disk. We find that a gravitationally and thermally unstable disk evolves, in a self-stabilizing manner, into a globally quasi-stable disk that consists of cold ($T < 100$ K), dense clumps and filaments surrounded by hot ($T > 10^4$ K), diffuse medium. In the quasi-stable phase where cold and dense clouds are formed, the effective stability parameter, Q, has a value in the range 2-5. The dynamic range of our multi-phase calculations is $10^6 - 10^7$ in both density and temperature. Phase diagrams for this turbulent medium are analyzed and discussed. We also succeeded in modeling star formation in the multi-phase ISM with 2 pc resolution. Massive stars formed in the dense, cold clouds are tracked for their life time, and finally explode as SNe. The filament-like structure of the cold gas is stable for the SNe, although bubbles of the hot gas ($T > 10^6$ K) are formed. We observed recurrent burst-like SNe production.

1. Introduction

We model the multi-phase and inhomogeneous interstellar medium (ISM) in the inner region of a galactic disk including fundamental physical processes crucial for understanding star formation, global and local dynamics of the ISM in galaxies, and aspects of galaxy formation such as feedback. Most numerical simulations of the ISM and of star formation in galaxies have assumed simpler ISM models, e.g. an isothermal or nearly-isothermal equation of state, and either a smooth medium or discrete clouds.

In the present paper, we report on the structure and global evolution of multi-phase ISM models in two-dimensions, taking into account self-gravity of the gas, galactic rotation, radiative cooling, and heating due to UV background radiation, SN explosions and stellar wind. We use an Eulerian hydro-code without periodic boundary conditions. Our code allow us to handle over seven orders of magnitude for density and temperature in a $\sim$ kpc-scale region around the galactic center with $\sim$ pc-scale resolution.

2. Numerical Method and Models

We solve the hydrodynamical equations and Poisson equation with an Euler mesh code (AUSM, see Liou & Steffen 1993). We use 1024^2 Cartesian grid points covering a 2 kpc $\times$ 2 kpc region. Therefore, the spatial resolution is 1.95 pc. The second-order leap-frog method is used for the time integration. We adopt implicit time integration for the cooling term.

The initial condition are an axisymmetric and rotationally supported disk with the Toomre stability parameter $Q = 1.2$ over the whole disk. Random density and temperature fluctuations are added to the initial disk. These fluctuations are less than 1 % of

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the unperturbed values. The initial temperature is set to 10^4 K over the whole region. We assume the gaseous disk is rotating in an axisymmetric, time-independent stellar potential. The mass of the gas disk is about 10 % of the stellar mass.

We take into account two feedback effects of massive stars on the gas dynamics namely stellar winds and supernova explosions. We first identify grids which satisfy criteria for star formation. The criteria are a surface density threshold for star formation $(\Sigma_g)_{i,j} > \Sigma_c$ and a critical temperature $(T_g)_{i,j} < T_c$ below which star formation is allowed. In these simulations we have chosen $T_c < 50K$ and $\Sigma_c = 5 \times 10^4 M_\odot$ pc^{-2}. We do not assume any global criteria for gravitational instability The stars radiate energy due to stellar winds during their lifetime which is approximately$\sim 10^7$ yr. When the star explodes as supernova an energy of 10^{51} ergs is injected into the mesh where the particle is located. The cooling procedure is not used for such meshes, but the meshes adjoining the supernova mesh are treated normally. With our code, the 2-D evolution of blastwaves caused by supernovae in an inhomogeneous medium with global rotation is followed explicitly. Therefore, we can follow consistently the thermal and dynamical evolution of the ISM around the star forming regions and the associated supernovae remnants and superbubbles.

3. Morphology and Evolution of the ISM

The most prominent feature of the resulting quasi-stable structure is its filamentary appearance (Fig.1). The high density clumps are embedded in less dense filaments ($\Sigma_g \sim 10^{3-4} M_\odot$ pc^{-2} and $T_g < 100$ K). The characteristic size of the highest density clouds ($\Sigma_g \geq 10^5 M_\odot$ pc^{-2}) is about 5-50 pc. The temperature of the very low density gas in the voids sometimes reaches 10^6 K, due to shock heating. The energy source of this heating is the turbulent, random motion of the gas, at velocities $\sim 10 - 100$ km s^{-1}.

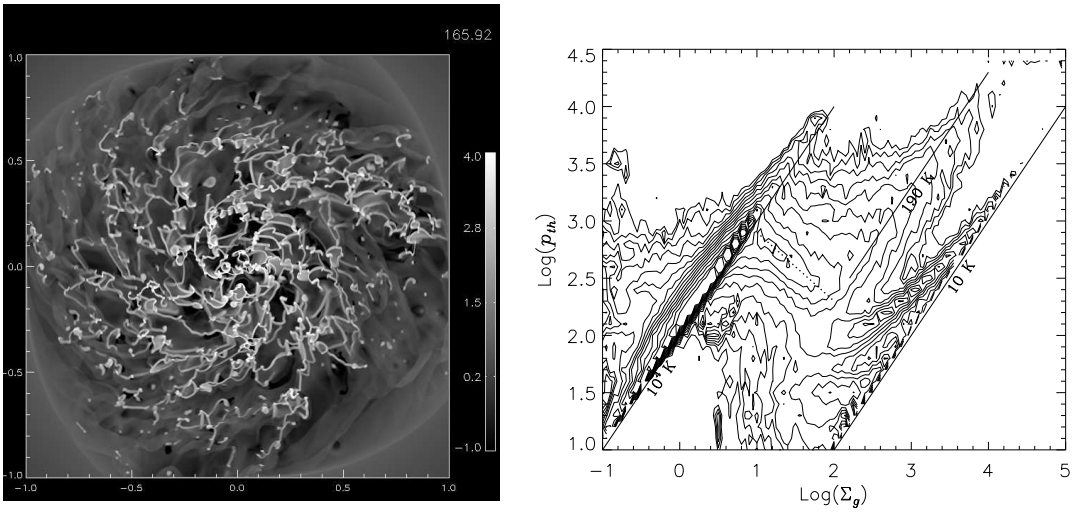

FIGURE 1. (left) Density map of a model without star formation at $t = 166$ Myr. The density range is 10^{-1} to $10^4 M_\odot$ pc^{-2}

FIGURE 2. (right) Pressure ($\Sigma_g T_g$) vs. density (Σ_g) phase diagram for the model shown in Fig. 1. Three diagonal lines show the gaseous temperature 10^4 K, 190 K, and 10 K. The dotted line means thermally unstable gas.

Figure 2 is a phase diagram ($p_{\rm th} \equiv \Sigma_g T_g$ vs. Σ_g) for the model shown in Fig.1. The

left and right diagonal lines correspond to states in which the gas temperature is 10^4 and 10 K. There are also two less prominent 'ridges' between the hot and cold phases, i.e. $(p_{\rm th}, \Sigma_g) = (3,1) - (2.5,2)$ and $(2.5,2) - (4,4)$. One ridge corresponds to filaments with temperature, $T_g \sim 200$ K. The second ridge indicated by a dotted line has 'negative γ' where γ is the adiabatic index. The gas in this state is thermally unstable. In spite of this instability the gas component does not have temporal variations. This is not a paradox, if we consider the kinematic or turbulent pressure of the gas as well as the thermal pressure. As can be seen in this phase diagram, the system cannot be described as a simple two- or three-phase media with pressure equilibrium between the phases.

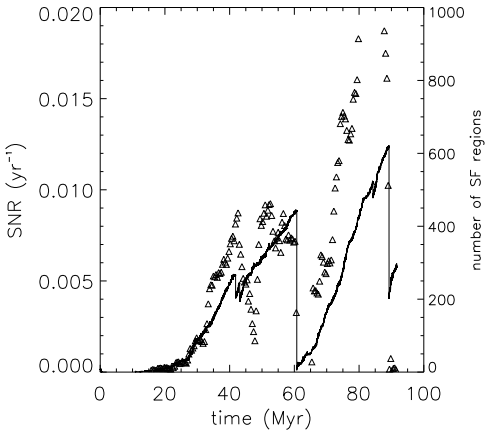

FIGURE 3. Time evolution of the SN rate (triangles) and the number of the star forming regions (solid line).

Although the initial Q value is 1.2 (i.e. the disk is stable for an axisymmetric modes), the effective Q value becomes much less than unity after a few Myr, because the cooling time is very short. The gas temperature decreases from the initial value ($\sim 10^4$ K) to an equilibrium temperature ($\sim 10^2$ K) within 10^5 yr. Since the initial density is higher in the central region of the disk than in the outer region, gravitational instabilities begin in the inner few 100 pc and develop outward. At $t \sim 10$ Myr ($\sim$ one rotational period at $R \sim 200$ pc), the gravitational instabilities in the central 500 pc are already in a non-linear phase, where the maximum density contrast is about 10^6. At $t \sim 25$ Myr, the instability grows non-linearly over the whole disk, and many clumps, filaments and low density voids are formed. At this stage, $Q_{\rm eff}$ increases above the marginal stability value for the whole disk. This means that the system is globally self-stabilized. We found that the stabilization is mostly due to the increase of the velocity dispersion of the gas.

About 80 % of the mass is in the cold ($T_g < 100$ K) phase. As expected, on the other hand, the volume filling factors of the hot, warm and cold gas indicate that the hot gas ($T_g \geq 9000$ K) occupies a volume $10^{2.5}$ times larger than the cold gas. The volume filling factor for the gas in the temperature range $11000 \leq T_g < 10^5$ K increases from 0 to 30% until $t = 30$ Myr. After 30 Myr, the volume filling factor of each component does not change appreciably, and this also shows that the system reaches a quasi- equilibrium state.

It is notable that the multi-phase, quasi-stable ISM is formed from a highly gravitationally and thermally unstable state without heating due to SNe. The diffuse UV heating does not contribute to the global stabilization. Shock heating is a dominant heating mechanism for $T_g > 10^4$ K in this system. Shearing of the disk induced by differential

rotation and gravitational perturbation from clumps are the main energy source for the shock heating.

We found in a model with star formation that the SNe cannot significantly change the multi-phase structure described above. The quasi-stationary, filamentary structure of the cold gas is almost the same as seen in the model without star formation, although very hot and diffuse gas ($T > 10^6$ K) is produced due to the SNe. It is hard to produce huge holes (> 100 pc) in a region occupied with many dense clumps/filaments. This is because the radiative cooling at the dense region is very effective. The SNe and blast waves, however, trigger new star formation at the dense clouds around them. Figure 3 is time evolution of the SN rate and the number of the star forming sites. Recurrent burst-like SNe production is clear. The period of the burst is about 10 Myr, which is the life time of massive stars. That is, one burst of SNe produces new massive stars, then they will explod after about 10 Myr.

4. Summary

We have shown that a globally stable, multi-phase ISM is formed as a natural consequence of the non-linear evolution of a self-gravitating gas disk. The gas is in so many and so various phases represented by a wide range of density and temperature that multi-phase is probably an inadequate description. The gas has properties more like a phase continuum. The density ranges over seven orders of magnitude from $10^{-1} - 10^6 M_\odot$ pc^{-2}, and the temperature extends from $10 - 10^8$K. We found that the ISM cannot be expressed simply by the two-phase or three-phase model (e.g. McKee & Ostriker 1977; Ikeuchi, Habe, & Tanaka 1984; Norman & Ikeuchi 1989; Norman & Ferrara 1996), because the gas dynamic processes, such as turbulence, global rotation, shear motion and shocks, are at least as important as thermal processes. Our high resolution Eulerian hydrodynamic code allows us to handle gas dynamics on a kiloparsec scale with a few parsec resolution regardless of the gas density. Possible star forming sites where the gas density is very high ($n > 10^4$ cm^{-3}) and the temperature is less than 100 K can be identified clearly, even if the disk is globally stable. The evolution of supernova remnants in an inhomogeneous and rotating media is fully followed, and supernovae themselves can triger new star formation in surrounding dense clouds.

Numerical computations were carried out on VPP300/16R at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan.

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