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Two and Three-dimensional Inhomogeneous Gas Dynamics in the Central Kpc

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Abstract. The parsec-scale structure of the interstellar medium (ISM) in the central kpc region is discussed based on our two and three dimensional high resolution hydrodynamical simulations, taking into account realistic cooling and self-gravity of the gas. Two-dimensional simulations of the ISM in a weak bar potential reveal that the resonant structures, such as spirals, have actually fine structure which could be observed with the next generation radio interferometer. Three dimensional structure of a massive gas disk in the central 100 pc is highly inhomogeneous. Diffuse plumes outsize the disk are formed due to supernovae. The density structure of the ISM is characterized by a "tangled network", which is a natural consequence of non-linear development of thermal and gravitational instability in a rotating system. The strong non-linearity of the evolution is also proved by the fact that the density PDF is well fitted by a single Log-Normal function over a wide range.

1. Introduction

The ISM in galaxies is multi-phase and inhomogeneous over a wide range of scales from sub-pc to kpc. Global and local star forming activity should be closely related to the structure of the ISM. However, the ISM in numerical simulations on galactic scales is often assumed to be a smooth, isothermal fluid or cloud complex with a constant velocity dispersion. For example, gaseous response to bi-symmetric gravitational potentials, such as stellar bars in galaxies, has been well studied numerically since the early 70's. However, almost all past simulations assumed a simple equation of state for the interstellar matter, namely isothermal gas of $\sim 10^4$ K, or equivalently a constant velocity dispersion of an ensemble of clouds. The isothermal approximation would be relevant for the large scale gas dynamics in galaxies. However, it is obvious that the inhomogeneity of the ISM should be taken into account in the galactic central region, where the system size is no longer large enough compared to the scale length of the inhomogeneous ISM.

Massive gas components whose total masses are $10^7 \sim 10^8 M_\odot$ are widely observed in the central kpc and sub-kpc regions of normal and barred spiral galaxies (Sakamoto at al. 1999a), Seyfert galaxies(Khono, in this volume), starbursts and Ultra Luminous InfraRed Galaxies (ULIRGs) (Scoville, in this volume). Such massive gas plays an important role for the nuclear activity such as nuclear starbursts, galactic superwind, and AGNs. However, the structure and dynamics of the nuclear massive gas disk and its relation with the star formation and fueling processes into the AGN region is yet to be understood. In order to investigate these points using numerical simulations, we need a more realistic treatment for the ISM than the isothermal gas approximation.

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 K $< T_g <$ 10^8K) and heating. A quasi-stable structure of the ISM was found where various temperature and density phases of the gases coexist, and the velocity field resembles compressible turbulence.

In this paper, we apply the numerical approach by Wada & Norman (2001) (WN01) to the gas dynamics in a weak barred potential, and see how the realistic treatment of the ISM changes the response of the ISM to the bar potential. We also explore the three-dimensional structure of a massive gas disk in the galactic central 100 pc region under the influence of frequent supernova explosions.

2. Methods and Models

2.1. Numecical Scheme

We solve numerically the hydrodynamical basic equations taking into account the self-gravity of the gas, radiative cooling, and heating processes. In order to investigate the effects of the global dynamics of the gas, the evolution of the whole rotating disk is simulated. The hydrodynamic scheme used here is AUSM (Advection Upstream Splitting Method), which is a high-accuracy explicit Eulerian code with non-adaptive grids. We achieve third-order spatial accuracy with MUSCL. The convolution method with the Fast Fourier Transform is used to solve the Poisson equation. We use the second-order leap-frog method for time integration and implicit time integration for the energy equation.

The effect of the radiative cooling is implemented using an implicit method with a cooling function between 10 K and 10^8 K, and Solar metalicity is assumed. We assume a uniform UV radiation field and photoelectric heating of grains and PAHs. More details on the numerical methods and test results are described in WN01.

2.2. Potential model and initial conditions of 2D models

The bar potential is modeled as $\Phi(R,\phi) = c^2/a(R^2+a^2)^{1/2}[1+\varepsilon(R)\cos 2(\phi - \Omega_p)]$, where $a = 200$ pc is the core radius of the potential, $v_{\rm max} = 150$ km s^{-1} is the maximum circular rotational speed, and $c \equiv v_{\rm max}(27/4)^{1/4}a$. $\varepsilon(R) \equiv \varepsilon_0 a R^2/(R^2+a^2)^{3/2}$. The parameter $\varepsilon_0 = 0.05 - 0.1$ represents the strength of the bar and, $\Omega_p = 140$ km s^{-1} kpc^{-2} denotes the pattern speed of the bar. With this pattern speed, the inner and outer ILRs are located at $R = 200$ and 400 pc.

We use 2048^2 Cartesian grid points for calculating gas dynamics in a 2 kpc$\times$ 2 kpc region which includes the galactic center. Therefore the spatial resolution is 0.98 pc.

The initial condition is an axisymmetric and rotationally supported disk whose radius is 1 kpc. Random density fluctuations are added to the initial disk, with an amplitude less than 1 % of the unperturbed density and tempera-

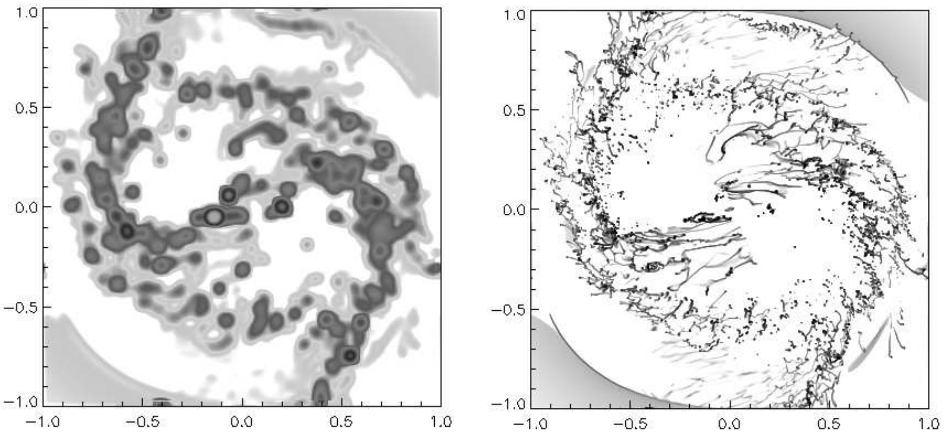

Figure 1. (left) Density distribution of the cold gas ($T_g < 100$ K) in a weak bar potential convolved with a 100 pc "beam" size. (right) Same as left, but with a 10 pc beam size. Unit of scale is kpc.

ture. The initial temperature is set to 10^4 K over the whole region. The initial rotational velocity is chosen in order to balance the centrifugal force caused by the gravitational potential.

2.3. Initial conditions for 3-D models

We use $512^2 \times 32$ Cartesian grid points covering a $256^2 \times 16$ pc^3 region. Therefore, the spatial resolution is 0.5 pc. The initial condition is an axisymmetric and rotationally supported thin disk with the total gas mass of $M_g = 5 \times 10^7 M_\odot$. Random density and temperature fluctuations are added to the initial disk. These fluctuations are less than 1 % of the unperturbed values and have an approximately white noise distribution. The initial temperature is set to 10^4 K over the whole region.

Supernova explosions are assumed to occurr at random positions in the region of $|x| < 115$ pc, $|y| < 115$ pc, and $|z| < 4$ pc. The average superanova rate is 0.2 yr^{-2} kpc^{-2}. The energy of 10^{51} ergs is injected into the cell as the thermal energy. In contrast to previous numerical studies of the ISM on a galaxy scale with supernovae explosions, we do not assume any evolutionary models for the SNR or for the heating efficiency of the ISM due to supernovae. With our code, the three-dimensional evolution of blast waves caused by supernovae in an inhomogeneous and non-stationary medium with global rotation is followed explicitly, taking into account the radiative cooling.

3. Results

3.1. 2-D structure of the ISM in a weak bar

Figure 1 (left) 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

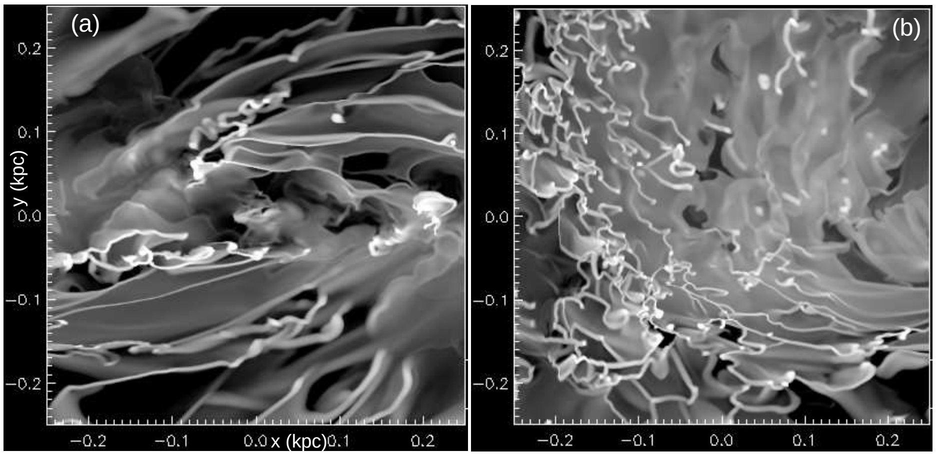

Figure 2. Density distribution of the same model in Fig. 1. (a) at the central 500 pc region, and (b) at the arm region. Gray scale represents log-scaled density. The maximum density contrast is 10^5. Unit of scale is kpc.

Interferometer, for example. Two clumpy trailing spirals are clear, and one might see a nuclear "pseudo ring". There are dense regions at the base of the spirals and at the nuclear region. Figure 1 (right) is the same as Fig. 1 (left), but with 10pc resolution. It is clear that spirals are actually ensamble of small clumps/filaments (see also Fig. 2(b)). We find from the comparison of the two maps that present day interferometers cannot not reveal the fine structure of the molecular gas in the central kpc of external galaxies. The nuclear "pseudo-ring" seen in the low resolution map is acturally several dense, compact clumps with filamentary structures (see also Fig. 2(a)). The dense small clumps in the nuclear region are typically $10^5 M_\odot$. The density range here is greater than 4 orders of magnitude. The closeup of the arm region (Fig. 2 (b)) reveals fine structure of a dense region of the arm. It is interesting that the density structure in the central and arm regions are very different.

By comparison with an ideal model, namely isothermal, non-self-gravity model, and the more realistic model of the ISM, we find that the effect of the resonances in the realistic, inhomogeneous ISM is less important than in the ideal model. The global morphology, such as the spirals, are reproduced in the ideal model, but on a small scale, the inhomogeneity of the ISM tends to erase the resonant structures.

3.2. 3-D Structure of a massive nuclear disk

Figure 3 (top) shows the density distribution of the disk in a quasi stable state (t = 4.3 Myr), where the volume rendering technique is used to visualize the three dimensional density field. Dense filaments/clumps form a "tangled net-

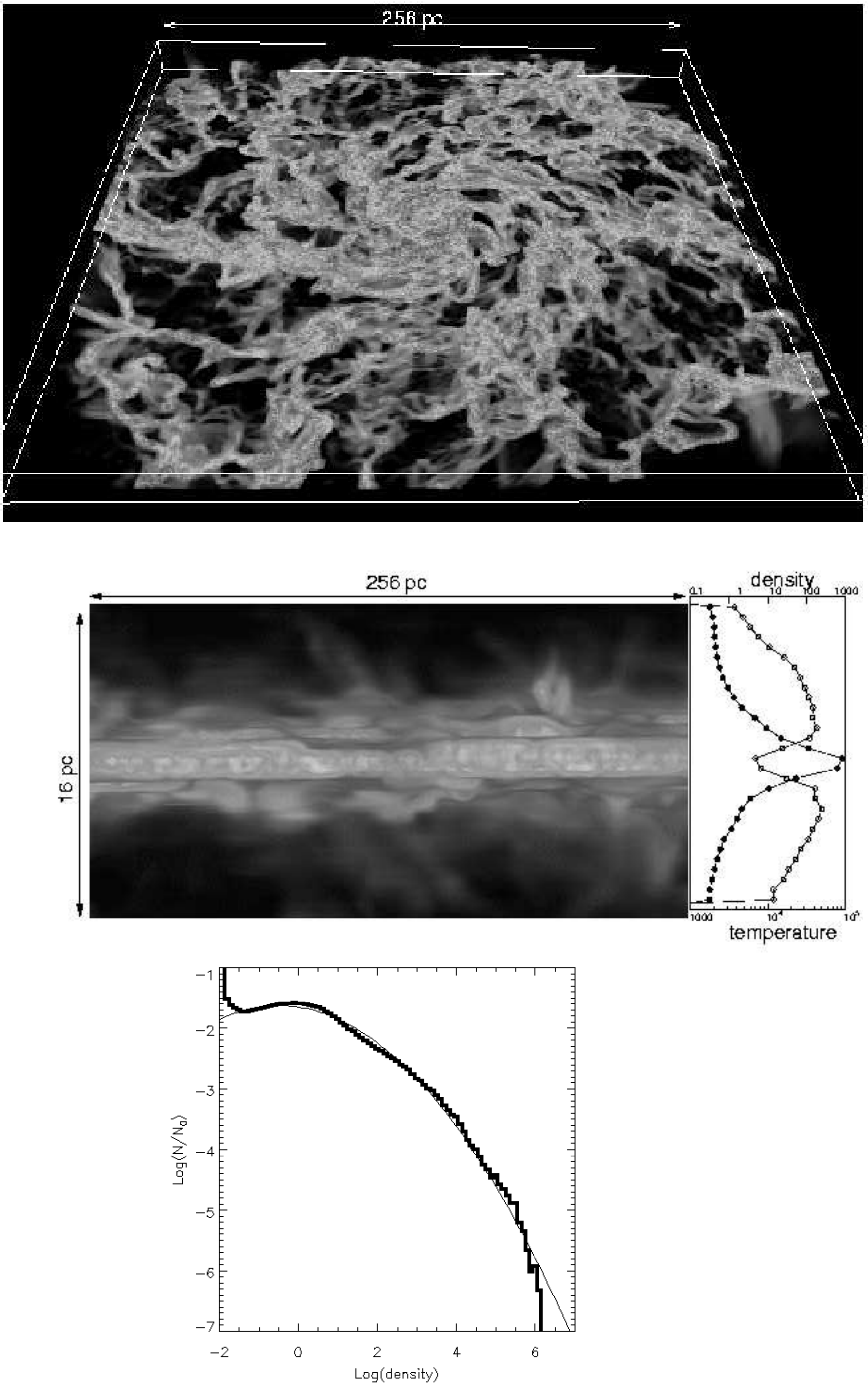

Figure 3. (Top) Density structure in a three-dimensional view. (Middle) Density structure in an edge-on view. Vertical distributions of density ($M_{\odot}$ pc^{-3}) and temperature (K) are also shown. (Bottom) Density probability distribution function (PDF).

work". Radial surface density distribution in the quasi-steady state is different from the initial uniform disk, and it is fitted on average by an exponetial profile: $\Sigma_g(R) \sim 200 e^{-R/R_0} M_\odot$ pc^{-2}, with $R_0 \sim 50$ pc. This is a consequence of the angular momentum transfer due to the turbulent motion in the disk. Velocity dispersion in the plane is $\sim 35 \pm 5$ km s^{-1} over the whole disk

Figure 3 (middle) is an edge-on view of the density distribution. Vertical distributions of average density and temperature show that the dense, cold gases form a geometrically thin disk, where the average temperature is about $8000 \sim 10^4$ K. The dense disk has a diffuse envelope, where the volume average temperature is about $3 - 4 \times 10^4$ K. Note that there are cold ($T_g < 100K$) gases in the disk, but they are clumpy, and occupy small volume. The diffuse gases form plume-like structures outside the dense disk, which are direct results of supernova explosions in the disk. The vertical structure is quasi-steady, that is, the kinetic and thermal heating due to supernovae balances with the radiative cooling followed by infall of the cooled gas towards the disk. This phenomena look like a miniature of the "galactic fountain".

Although the 3-D spatial structure of the density looks quite complicated, statistically the system is rather simple. In Fig. 3 (bottom), we plot the probability distribution function of the density, i.e. a histogram of volume as a function of the gas density. The PDF can be fitted very well by a single Log-Normal function between $\rho \sim 10^{-2} \sim 10^6 M_\odot$ pc^{-3}. WN01 reported Log-Normal density PDF in 2-D models for high density regions over about 4 orders of magnitude, and a Normal function for low density regions. Here we do not find that the PDF for low density regions obeys the Normal distribution. The Log-Normal PDF implies that the system is formed through highly non-linear and random processes, i.e. gravitational instability of the dense disk, turbulent shear, and shock compressions due to supernovae.

The density structure of the massive disk with supernovae is interesting in terms of the starburst-AGN connection. If the gas system around the AGN is inhomogeneous as seen in the present model, then the nucleus could be obscured by the dense clumps and filaments for a certain lines-of-sight. The turbulent motion in the disk causes mass inflow towards the nucleus, and the accretion rate would be time dependent, and also depends on the star formation rate in the disk (Wada & Norman, in preparation).

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