THE THREE-DIMENSIONAL STRUCTURE OF A MASSIVE GAS DISK IN THE GALACTIC CENTRAL REGION

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ABSTRACT

Using high-resolution, three-dimensional hydrodynamical simulations, we investigate the structure of the interstellar medium (ISM) in the central 100 pc region in galaxies, taking into account the self-gravity of the gas, radiative cooling from 10 to 10⁸ K, and energy feedback from supernovae. Similar to the previous two-dimensional results produced by Wada and Norman, we find that a gravitationally and thermally unstable ISM evolves, in a self-stabilizing manner, into a quasi-stable thin disk, which is characterized by a network of cold (T < 100 K) dense clumps and filaments, and a hot (T > 10⁶ K) diffuse medium. Supernova explosions blow the diffuse gases from the disk, and as a result, a quasi-steady diffuse halo, which is not uniform but has a plumelike structure, is formed. The density probability distribution function in a quasi-steady state is well fitted by a lognormal function over about 7 orders of magnitude.

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

1. INTRODUCTION

Massive gas components whose total masses are 10⁷–10⁸ M☉ are widely observed in the central kiloparsec and subkiloparsec regions of various galaxies. Such a massive gas component plays an important role in nuclear activity such as nuclear starbursts, galactic superwinds, and active galactic nuclei (AGNs). However, the structure of the massive gas disk or its relation to star formation and fueling processes in the AGN region is not yet understood. For example, the millimeter interferometers do not have a fine enough spatial resolution to reveal the detailed structure of the molecular gas in the central 100 pc region of nearby galaxies. Hopefully, this situation will change drastically in the next decade; using the next-generation millimeter and submillimeter interferometer (the Atacama Large Millimeter Array), the spatial resolution is improved to ~0.01 pc, and we expect to be able to know parsec-scale structures of the molecular gas in the central regions of nearby galaxies. On the other hand, our theoretical understanding of the interstellar medium (ISM) in the central subkiloparsec region is still insufficient. The ISM in the central region should not simply be approximated as a one-phase fluid or an ensemble of discrete clumps. We should use a more realistic treatment for the ISM in the central region in order to reveal how the structure of the ISM relates to the nuclear activity.

Recently, Wada & Norman (1999, 2001, hereafter WN99, WN01) presented high-resolution, two-dimensional numerical models of the ISM in a kiloparsec-scale galactic disk, in which they numerically solve hydrodynamical equations and the Poisson equation with realistic radiative cooling and heating. Star formation and its energy feedback on the ISM are implemented in their numerical code. They found a quasi-stable structure of the ISM where various temperatures and density phases of the gases coexist. Its velocity field resembles that of compressible turbulence. However, the two-dimensional approximation used in WN01 would not be relevant for the three-dimensional ISM, especially for the vertical structure of the hot gas component (Rosen & Bregman 1995; Korpi et al. 1999) in the central region of galaxies.

In this Letter, we report on a first attempt to understand the three-dimensional structure of the ISM in the galactic central region, taking into account the self-gravity of the gas, galactic differential rotation, radiative cooling, and heating due to UV background radiation and supernova (SN) explosions.

2. NUMERICAL METHOD AND MODELS

The numerical methods are basically the same as those described in WN01. Here we briefly summarize them. We solve the following equations numerically in three dimensions to simulate the evolution of a rotating ISM in a fixed gravitational potential:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} + \nabla p + \nabla \Phi_{\text{ext}} + \nabla \Phi_{\text{gg}} = 0, \quad (2)
\]

\[
\frac{\partial E}{\partial t} + \frac{1}{\rho} \nabla \cdot [\rho (\mathbf{E} + p) \mathbf{v}] = \Gamma_{\text{UV}} + \Gamma_\ast - \rho \Delta(T_\ast), \quad (3)
\]

\[
\nabla^2 \Phi_{\text{gg}} = 4\pi G \rho, \quad (4)
\]

where \(\rho, p, \mathbf{v}\) are the density, pressure, and velocity of the gas, respectively, and the specific total energy \(E = |\mathbf{v}|^2/2 + p(\gamma-1)\rho\), with \(\gamma = 5/3\). We assume a time-independent external potential \(\Phi_{\text{ext}} = -(27/4)\nu^3/(r^2 + a^2)^{1/2}\), where \(a = 10\) pc is the core radius of the potential and \(\nu = 100\) km s⁻¹ is the maximum rotational velocity. We also assume a cooling function \(\Delta(T_\ast) = 10^7 < T_\ast < 10^8\) K (Spaans & Norman 1997) with the solar metallicity and heating due to photoelectric heating (\(\Gamma_\ast\)) and to energy feedback from SNe (\(\Gamma_{\text{SN}}\)). We assume a uniform UV radiation field, which is 10 times larger than the local UV field (Gerritsen & Icke 1997): \(\Gamma_{\text{UV}} = 1.0 \times 10^{-23} \epsilon G_\odot\) ergs s⁻¹, where the heating efficiency \(\epsilon\) is assumed to be 0.05 and \(G_\odot\) is the incident far-UV field normalized to the local interstellar value.

The hydrodynamic part of the basic equations is solved by the Advection Upstream Splitting Method (Liou & Steffen 1993). We use 512 × 32 Cartesian grid points covering a 256 × 16 pc³ region around the galactic center. Therefore, the spatial resolution is 0.5 pc. The Poisson equation is solved in order to calculate the self-gravity of the gas using the fast...
A typical run is about 30 hr using a vector parallel supercomputer. The duration and structure of the SNe, depends on the gas density distribution around the SN. Computational time for one SN explosion is 4.8 yr kpc⁻¹, which is as high as that in nuclear starbursts (Kennicutt 1998). The energy of 10⁵¹ ergs is instantaneously injected into a single cell as thermal energy. During the calculation (∼5 Myr), about 10⁷ SNe explode. We do not assume simple evolutionary models for each supernova remnant (SNR) or for the heating efficiency of the ISM due to SNe. The three-dimensional evolution of blast waves caused by SNe in an inhomogeneous and nonstationary medium with global rotation is followed explicitly, taking into account the radiative cooling followed by the infall of the cooled gas toward the disk. It looks like a miniature of the “galactic fountain” model (Shapiro & Field 1976; Habe & Ikeuchi 1980).

It would be useful to estimate a typical radius of an SNR in order to understand what causes the density structure. A radiative SNR goes into a pressure-driven snowplow (PDS) phase when the radius of the SNR is \( R ∼ 0.6(ρ/100 M_\odot \text{pc}^{-3})^{-1/2} \) pc (Cioffi & Shull 1991). The maximum radius of the shell at the end of the snowplow phase is \( R_{s,\text{max}} = 80 P_{s,\text{app}}^{-1/5} \rho_{g,\text{app}}^{-1/5} \) pc, where the ambient pressure \( P_{s,\text{app}} = P/(k_B T_{\text{app}}) \). The velocity field of the medium is turbulent-like because of the random energy input from SN explosions, and the vertical rms velocity is \( v_{\text{rms}} ∼ 10 \text{ km s}^{-1} \), which is comparable to that estimated from the evolution of the shock velocity of an SNR (\( \propto t^{2/5} \)) after a 1 Myr evolution. If we use the turbulent pressure \( \rho v_{\text{rms}}^2 \) as \( P_{s,\text{app}} = R_{s,\text{max}} ∼ 3 \) pc. Since \( R_{s,\text{app}} \propto t^{2/7} \) at the PDS phase, the remnant reaches its maximum size at \( t ∼ 1 \) Myr. The above estimate implies that the SNRs cannot be larger than 1 pc near the disk plane where the average density is much greater than 100 \( M_\odot \text{pc}^{-2} \). SNRs that explode at several parsecs above the disk plane may cause 10 pc scale vertical
structures, as seen in the right panel of Figure 1. Note that the present spatial resolution (0.5 pc) might not be fine enough to resolve the early evolution of SNRs in very dense regions.

Figures 2a and 2b are the temperature distribution at the disk plane ($z = 0$) and at $z = 4$ pc, respectively, at $t = 5.2$ Myr. In the disk plane, most gases are in a cold ($T < 100$ K) phase, while, on the other hand, warm ($10^3$ K $> T > 10^2$ K) and hot ($T > 10^3$ K) phases create a patchy morphology above the disk plane. The hot gas originates in SN explosions. The UV radiation helps to form the warm diffuse gas, but it does not significantly affect the gasdynamics. Since the radiative cooling in the dense regions near $z = 0$ is effective, the SNRs are less prominent near the disk plane than in the halo region.

Although the spatial structure of the density is quite complicated, as seen in Figure 1, statistically the system is rather simple. In Figure 3, we plot the probability distribution function (PDF) of the density, i.e., a histogram of volume as a function of the gas density. The PDF is well fitted by a single lognormal function over about 7 orders of magnitude between $\rho = 10^{-3}$ and $10^3 M_\odot$ pc$^{-3}$, which suggests strong nonlinearity in the formation process.

Figure 4 is the volume-weighted temperature PDF. There are two dominant phases at $T \sim 50$ and $10^4$ K, which are thermally stable phases determined by the cooling functions (see Fig. 1 in WN01). The cold gas around $T \sim 50$ K corresponds to the point $d \log \Lambda/\log T \sim 2$, above which the system is expected to be thermally unstable (Schwarz, McCray, & Stein 1972). There are also small peaks at $T \sim 7 \times 10^4$ and $\sim 10^6$ K. The latter is a direct result of SN explosions. The system roughly shows three phases in temperature. It should be noted, however, that a considerable amount gas exists between the cold and warm phases that are thermally unstable.
regimes. This cannot be understood by the behavior of multiphase gas in pressure equilibrium but as a consequence of turbulent motions in the medium. As in the two-dimensional case (see Fig. 13 in WN01), the thermal pressure is dominated by turbulent pressure in this system. Vázquez-Semadeni, Gazol, & Scalo (2000) concluded from their two-dimensional simulations that the turbulence smears out the thermal phases, creating a continuous distribution of the physical properties. This is consistent with our three-dimensional results.

4. DISCUSSION

We have examined the three-dimensional density and temperature structure of a massive gas component in the central 100 pc region of a galaxy. We found that a globally stable, multiphase disk is formed as a natural consequence of nonlinear evolution. The structure is similar to what has previously been found in two-dimensional simulations for a kiloparsec-scale disk (WN99; WN01). The SN explosions are assumed to be as high as those in nuclear starbursts, but they do not drastically change the intrinsically inhomogeneous “tangled” network density structure near the disk plane (z = 0). However, the SNe are important in producing the vertical structure, i.e., the diffuse filamentary halo (ρ ~ 10−10 M⊙ pc−3), and the hot component (T ~ 106 K). We also found that the density PDF is well fitted by a single lognormal function over about 7 orders of magnitude. This suggests that the density structure is dominated by a highly nonlinear process from low- to high-density regimes (Vázquez-Semadeni 1994).

PDFs have been discussed in relation to the structure of the turbulent ISM. Nordlund & Padoan (1999) indicated a formal proof for the lognormal PDF in isothermal supersonic turbulence. They also showed numerically that the lognormal PDF appears in three-dimensional isothermal, non-self-gravitating supersonic turbulence over about 3 orders of magnitude. In our system, on the other hand, thermal and gravitational instabilities play an important role in producing the very dense regions. The PDF can be fitted by a lognormal function over 7 orders of magnitude. Therefore, we believe that the isothermality is not a necessary condition for the lognormal PDF but is a natural feature of the highly nonlinear and random processes, which are achieved in the system that we are investigating, i.e., the self-gravitating, supersonic turbulence with radiative cooling and stellar energy feedback. However, an important open question remains: What determines the “width” of the lognormal PDF? Nordlund & Padoan (1999) suggested that the standard deviation of the lognormal PDF measures the mean rate of change of the density or rms Mach number of the turbulence. Since the density range in which the lognormal PDF is achieved in our system is quite large and since the self-gravity of the gas is crucial for yielding the very high density regions, it is not likely that the rms Mach number is the only parameter needed to determine the width of the lognormal PDF. WN01 reported that the density PDF in two-dimensional models can be fitted with a lognormal function for a high-density region over about 4 orders of magnitude but that the low-density part is fitted by a normal function. In the present three-dimensional model, we do not find that the PDF for a low-density region obeys the normal distribution. The difference between the two-dimensional and three-dimensional results would suggest that the third dimension is more important for less dense gases.

Finally, the density structure of the massive disk with SNe 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 from a certain line of sight. The turbulent motion in the disk causes mass inflow toward the nucleus, and the accretion rate would be time-dependent and would also depend on the star formation rate in the disk (K. Wada & C. Norman 2001, in preparation).

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