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Turbulence Driven by Supernova Explosions in a Radiatively-Cooling Magnetized Interstellar Medium

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ABSTRACT

We study the properties of supernova (SN) driven interstellar turbulence with a numerical magnetohydrodynamic (MHD) model. Calculations were done using the RIEMANN framework for MHD, which is highly suited for astrophysical flows because it tracks shocks using a Riemann solver and ensures pressure positivity and a divergence-free magnetic field. We start our simulations with a uniform density threaded by a uniform magnetic field. A simplified radiative cooling curve and a constant heating rate are also included. In this radiatively-cooling magnetized medium, we explode SNe one at a time at randomly chosen positions with SN explosion rates equal to and 12 times higher than the Galactic value. The evolution of the system is basically determined by the input energy of SN explosions and the output energy of radiative cooling. We follow the simulations to the point where the total energy of the system, as well as thermal, kinetic, and magnetic energy individually, has reached a quasi-stationary value. From the numerical experiments, we find that: i) both thermal and dynamical processes are important in determining the phases of the interstellar medium, and ii) the power index n of the B-ρ^n relation is consistent with observed values.

Key Words : Turbulence, ISM: Kinematics and Dynamics, ISM: Magnetic Fields

I. INTRODUCTION

It is well-known that i) the velocity dispersion of molecular clouds is much larger than their sound speed, but comparable to the Alfvén speed, and ii) the lifetime of molecular clouds appears far longer than their Jeans' collapse time (Blitz & Shu 1980, but see the arguments for much shorter lifetimes by Ballesteros-Paredes, Hartmann, & Vázquez-Semadeni 1999). This led Arons & Max (1975) to suggest that the turbulence seen in molecular clouds is maintained by lossless linear Alfvén waves, that could provide support against gravity. Recent development of computer technology and algorithms has enabled a few groups to test this idea. Compressible magnetohydrodynamic (MHD) turbulence simulations (Balsara et al 1998; Mac Low et al. 1998; Stone et al. 1998) show that the decay times of turbulence are comparable to the eddy turn-over time or even smaller. This means that the turbulence cannot be due to the initial formation of the cloud. Either clouds must be very short-lived, or they are kept in a turbulent state by driving. This driving is likely due to localized sources such as supernova (SN) explosions, stellar winds, etc, which now draw the attention of people.

The conventional picture of the discrete phases (e.g., McKee & Ostriker 1977) of the interstellar gas is recently challenged by both observational and theoretical studies. With newly obtained Arecibo data, Heiles (2001) showed that a large fraction of the warm and cold neutral medium is found in thermally unstable temperature regions. Through two-dimensional MHD simulations including cooling and heating processes, self-gravity, and energy injection from OB stars (without SN explosions), Gazol et al. (2001) confirmed his observational result.

In this paper, following an alternative idea, we take the SN explosions, which were ignored in Gazol et al. (2001), as a primary driving source, and simulate the evolution of radiatively cooling, magnetized interstellar gas. Based on the numerical models, we address the issue of the phases of the interstellar gas, and the properties of the SN-driven turbulence.

II. NUMERICAL METHOD AND PARAMETERS

The numerical calculations were done using the RIEMANN framework for computational astrophysics, which is based on higher-order Godunov schemes for MHD (Roe and Balsara 1996; Balsara 1998a,b), and incorporates schemes for pressure positivity (Balsara & Spicer 1999a), and divergence-free magnetic fields, (Balsara & Spicer 1999b). We solve the ideal MHD equations including both radiative cooling and pervasive heating in a $(200\ \mathrm{pc})^3$ periodic computational box, using a grid of 128^3 cells. We start the simulations with a uniform density of $\rho_0 = 2.3 \times 10^{-24}$ g cm^{-3}, threaded by a uniform magnetic field in the x-direction with strength $B_0 = 5.8\ \mu$G.

For the cooling, we use a tabulated version of the radiative cooling curve shown in Figure 1 of MacDonald and Bailey (1981), which is based on the work of Raymond, Cox & Smith (1976) and Shapiro and Moore

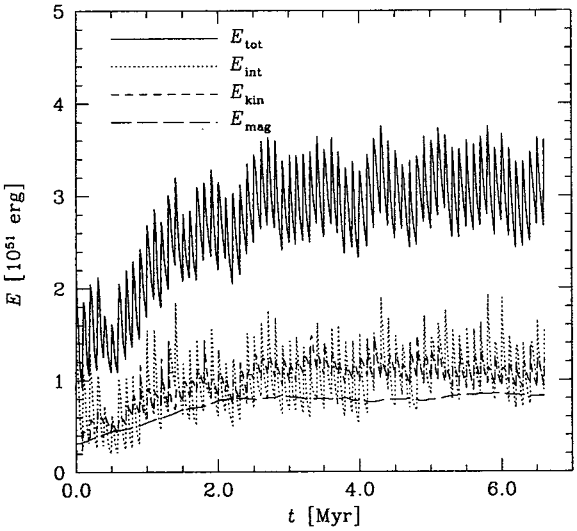

Fig. 1.— Time history of the thermal, kinetic, magnetic, and total energies. The supernova explosion rate used is twelve times larger than the Galactic value.

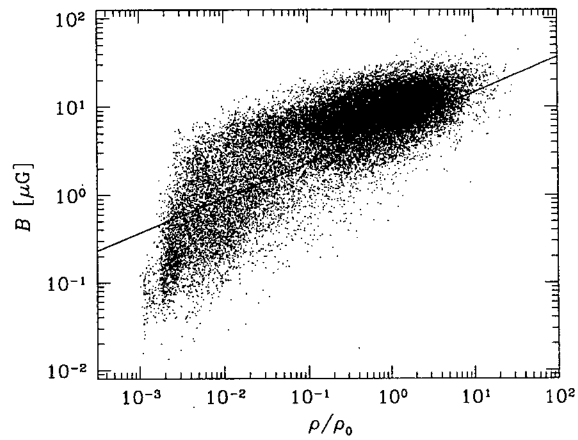

Fig. 2.— A scatter plot of the magnetic field strength as a function of normalized density at 6.6 Myr.

(1976). In order to prevent the gas from cooling below zero, we set the lower temperature cutoff for the cooling at 100 K. We also include a diffuse heating term to represent processes such as photoelectric heating by starlight, which we set constant in both space and time. We set the heating level such that the initial equilibrium temperature determined by heating and cooling balance is 3000 K. Since the cooling time is usually shorter than the dynamical time, we adopt implicit time integration for the cooling and heating terms.

We explode SNe with two different explosion rates: one with our present Galactic rate, and the other at a 12 times higher rate. The latter case might correspond to a mild starburst like M82, and is the case mostly described in this short paper. The SNe are permitted to explode at random positions. To avoid extremely high initial expansion velocities, we do not allow SNe to explode in regions with density less than 0.1 cm^{-3}. Each SN explosion dumps 10^{51} erg thermal energy into a sphere with radius 5 pc.

III. RESULTS

The easiest way to understand what's going on in our computational box is to look at energetics. Fig. 1 shows time history of thermal, kinetic, magnetic and total energies for the case with the 12 × higher SN rate. After around $t = 2.5$ Myr, the total energy attains a steady state. This means the input energy by SN explosions and the heating is balanced by the output energy by the cooling. Another interesting point is that the three energies are nearly in equipartition. Even though the SN explosion energy initially consists entirely of thermal energy, a fraction of it is transformed into kinetic and magnetic energies, and so the three energy components have nearly equal levels.

Fig. 2 shows the scatter plot of the magnetic field strength as a function of density at 6.6 Myr. Initially, we started the simulation with a pair of field and density values ($B_0 = 5.8\mu$G, $\rho/\rho_0 = 1$). Then thermal and dynamical processes broaden the distribution of these variables in such a way that denser regions have stronger field strengths and rarefied regions weaker strengths. This is because the system evolves while maintaining the rough equipartition between magnetic and kinetic energies, as shown above (Chandrasekhar-Fermi theory). We draw a line with an observed power index $n = 0.4$ of $B \sim \rho^n$. It seems that, at least, the upper envelope of the scatter plot follows the observed slope.

Fig. 3 shows the volume-weighted histograms of density, temperature, and pressure at three different time epochs, 4.0, 6.0, and 6.6 Myr. Since the system has already reached its steady state at these times, the three histograms in each panel are not much different from each other. Density (left panel) and temperature (center panel) histograms clearly show bi-modal distributions that may be matched to hot and warm phases. (The cold phase did not emerge because a simple extrapolated cooling curve was used to low temperature regions that did not include a region of thermal instability.) However, the broad distributions of density and temperature in each phase have different characteristics from those of a conventional multi-phase model. The pressure (right panel) also varies over more than an order of magnitude. (More detailed description of the pressure distribution is presented in Mac Low et al. 2001.) In the dynamical setting, like our model, of the interstellar gas with cooling and heating processes, the thermal process determines the most probable density, temperature and pressure, but the dynamical process broadens their distributions. The dynamical process even enables gas to have physical quantities that reside in the unstable domain of the thermal process.

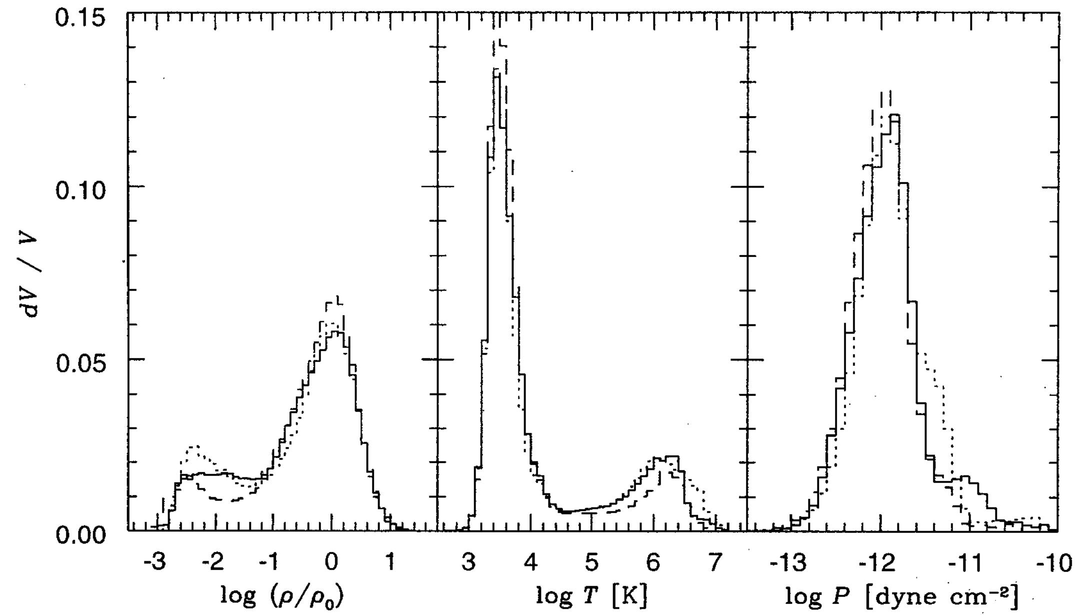

Fig. 3.— The volume fractions (or histograms) of density (left), temperature (center), and pressure (right). Solid, dotted, and dashed lines at each panel represent the fractions at 6.6, 6.0 and 4.0 Myr, respectively.

We also keep track of the temporal evolution of the volume filling factor of the hot gas whose logarithmic temperature is higher than 5.5, and find that the factor is sensitively dependent upon the SN explosion rates. It is about 2% with the Galactic rate, but 20% with the 12 times higher rate. Our value is certainly an underestimate, however, because we didn't take into account the stratified disk, we forced all SNe to occur in regions of density greater than 0.1 cm^{-3}, increasing their early cooling, and the densities in our initial high-energy spheres were so high that prompt radiative cooling was far more efficient than expected physically.

IV. CONCLUSION

From a numerical model of radiatively-cooling, turbulent, interstellar gas driven by SN explosions, we draw the following conclusions: i) Both thermal and dynamical processes play an important role in determining interstellar phases. Especially, the addition of the dynamical process drives conventional discrete phases into a continuous distribution of physical quantities. ii) The variation of magnetic field with density (power index 0.4) is consistent with Chandrasekhar-Fermi theory and observations.

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