SPATIAL PATTERN FORMATION OF INTERSTELLAR MEDIUM

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Abstract. Population dynamics of multi-phased interstellar medium (ISM) is investigated by using the lattice model in position-fixed reaction. Interactions between three distinct phases of gas, cold clouds, warm gas, and hot gas give rise to cyclic phase changes in ISM. Such local phase changes are propagated in space, and stochastic steady-state spatial pattern is finally achieved. We obtain the following two characteristic patterns:

(1) When the sweeping rate of a warm gas into a cold component is relatively high, cold clouds associated with warm gas form small-scale clumps and are dispersively distributed, whereas hot gas covers large fraction of space.

(2) When the sweeping rate is relatively low, in contrast, warm gas and cold clouds are diffusively and equally distributed, while hot gas component is substantially localized.

1. Introduction

Interstellar medium (ISM) is thought to be composed of multi-phased gas (for a review, see Ikeuchi 1988). The understanding of ISM has made revolutionary development when McKee and Ostriker (1977) proposed the three-phase model for ISM. They inferred the coexistence of hot gas (HG) with temperature $T = 10^5 - 10^6$ K, intercloud gas (or warm gas, WG) with temperature $T \sim 10^4$ K, and HI clouds (or cold cloud, CC) with $T \sim 100$ K in pressure equilibrium.

These three components of gas cannot be in static equilibrium. Ikeuchi and Tomita (1983) investigated phase changes between distinct phases of ISM. However, spatial propagation of such phase changes are not described in their model, which treats systems in mean-field approximation. To obtain mass density dynamics, such as clumping or dispersive behavior of HG, we need to study spatial pattern formation of the fundamental phase changes in ISM. This is the main aim of this paper.

2. Physical Assumptions and Basic Equations

To study spatial pattern formation, we use the position-fixed reaction model (Tainaka 1988). The rate equations for each phase of gas are then;

$$\frac{dX_{\rm C}}{dt} = AX_{\rm W} - PP_{\rm CH}, \tag{1}$$

$$\frac{dX_{\rm H}}{dt} = PP_{\rm CH} - P_{\rm HW}, \tag{2}$$

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$$\frac{dX_W}{dt} = P_{HW} - AX_W, \tag{3}$$

where A and P are numerical constants, X_C, X_W, and X_H represent the mass densities of CC, WG, HG, respectively, and $X_C + X_W + X_H = 1$, and P_{ij} denotes the joint probability that a species j lies in the nearest neighbor of a species i [i, j = C (cold cloud), W (warm gas), or H (hot gas)]. The relation $P_{ij} = P_{ji}$ thus holds. For details of the methods of simulations, see Tainaka et al. (1992).

3. Mean-Field Theory (MFT)

In the mean-field theory (MFT), we may write

$$P_{ij} = X_i X_j, \tag{4}$$

where i, j, k are one of (CC, WG, HG). By inserting equation (4) into basic equations (1)–(3) and by setting all the time derivatives to be zero, we obtain stationary solutions in MFT as,

$$X_{C,0} = \frac{1-A}{1+P}, \tag{5}$$

$$X_{H,0} = A, \tag{6}$$

$$X_{W,0} = \frac{P(1-A)}{1+P}. \tag{7}$$

It is rather easy to show that this is a stable solution as long as $0 \leq A \leq 1$.

4. Simulation Results

We fix $P = 1$ and change A (sweeping rate of a warm gas into a cold component) between 0 and 1. When A is relatively large, clustering behavior of CC is remarkable. Moreover, CC tends to surround WG, and HG is diffusively distributed. When A is relatively low, in contrast, HG begins to form one-dimensional cluster (chain structure), whereas mass densities of CC and WG increase.

Figure 1 depicts how mass fractions change as functions of A. The mean-field approximation requires that the mass densities of CC and WG should be the same when $P = 1$ (see equations 5–7). The simulation results, however, show a clear tendency that X_W also decreases together with the decrease in X_H as A decreases.

Global dynamics of phase changes in ISM leads to a paradox. It is obvious that the density of WG, X_W, decreases, as the sweeping rate (A) increases,

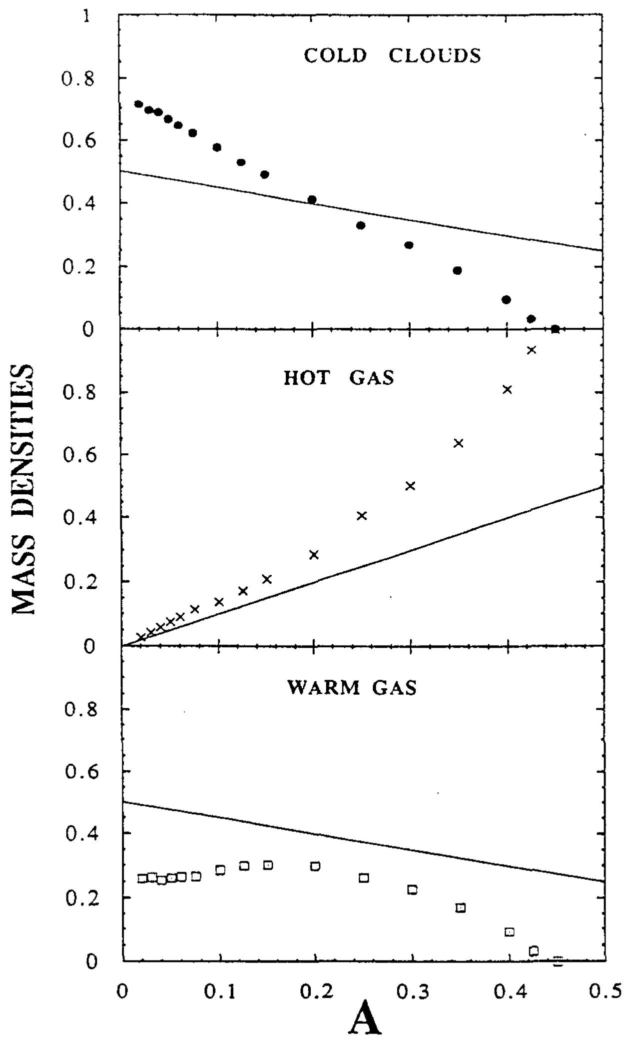

Fig. 1. Mass fraction of each component of gas as a function of A. The solid lines are the result of mean-field theory (MFT).

because WG is transformed into CC. However, we found that even when A decreases towards zero, X_W again decreases. This can be understood in terms of clumping behavior of HG. Note that WG is created from HG via collision. When A is very small, HG generates clumping structure so that WG has less chance to collide with HG than the case that HG is dispersively distributed. This phenomena cannot be predicted nor explained by the mean-field theory.

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5. Conclusion

We have developed the dynamical theory for the phase changes of the three-phased ISM. We find distinct features in its population dynamics which is not yet known in the mean-field theory. Especially, clumping behavior of HG is responsible for such qualitative discrepancy. The investigation of such global pattern formation is thus essential to understand the population dynamics.

The numerical computations were performed on Hitac M660H at Computer Center of Ibaraki University.

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