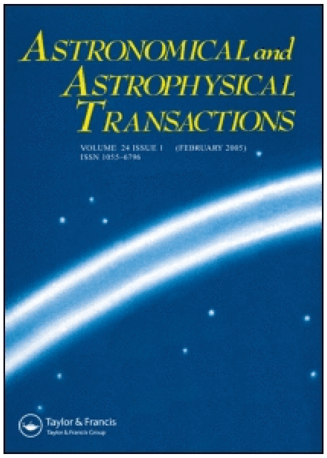

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ON INTERSTELLAR CLOUD FORMATION DUE TO THERMAL INSTABILITY

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The condensation mode of thermal instability is studied as a possible mechanism of interstellar cloud formation. It is shown that perturbations with characteristic dynamical time smaller than the cooling time evolve to develop hydrodynamical motions corresponding in general to the acoustic mode which prevents perturbations to condense quietly into clouds. The condensation mode is shown to be driven by thermal instability for a special choice of initial conditions for hydrodynamic variables. Perturbations of sufficiently large wavelength are shown to evolve to a dynamical state similar to the condensation mode independently of the form of the initial perturbations. Possible applications to the interstellar gas and the gas of cooling flows are indicated.

KEY WORDS Thermal instability, interstellar clouds

1 INTRODUCTION

Thermal instability is assumed to be one of the basic mechanisms which causes the interstellar gas (ISG) to be transformed into a multiphase state (Field, 1965; Pikelner, 1967; Field *et al.*, 1969). The basic idea is that under appropriate conditions thermal instability drives a monophase homogeneous medium to be separated into two components, viz. clouds and intercloud gas, which are in pressure equilibrium with each other. Field (1965) argued that the condensation mode of thermal instability which corresponds to quietly evolving isobaric perturbations governs such a phase transition. Qualitative physical understanding of this mechanism can be obtained from a simplified description of the energy balance in a given volume of the ISG. Assuming initial perturbations to be isobaric ($\delta P \propto \delta(\rho T) = 0$), and perturbed hydrodynamical motions subsonic ($v \ll c$) one can write for small temperature perturbations δT:

$$\frac{R}{\mu}\frac{d\delta T}{dt} = -(\gamma - 1)\left(\frac{d\mathcal{L}}{\partial T}\right)_P \delta T, \tag{1}$$

where $\mathcal{L} = \mathcal{L}(\rho, T) = \rho L(T) - G$, is the generalized cooling function, G is the heating rate by an external energy source (e.g., cosmic rays or X-rays) which is assumed to be independent of temperature and density, c is the sound speed, R is the gas constant, μ is the effective molecular mass; the other symbols have the common meaning. Therefore, small perturbations are unstable when

$$\left(\frac{\partial \mathcal{L}}{dT}\right)_P < 0, \text{ or equivalenty } T\left(\frac{\partial \mathcal{L}}{\partial T}\right)_\rho < \rho\left(\frac{\partial \mathcal{L}}{\partial \rho}\right)_T .$$

This relation has a clear meaning: for isobaric perturbations, $\delta T/T = -\delta\rho/\rho$, increase in density leads to larger radiative energy losses, and thus, if the temperature dependence of the cooling function $\mathcal{L}(T)$ is sufficiently weak, a depression of cooling rate due to the decrease in temperature is unable to balance these losses. As a result, the gas continues to cool progressively.

A comprehensive, rigorous study of thermal instability given by Field (1965) showed that the growth rate of the condensation mode is equal exactly to $n = -\mu(\gamma-1)(\partial\mathcal{L}/\partial T)_P/R$ which appeares on the r.h.s. of the approximate equation (1) in the short-wavelength limit $\lambda/c \ll \tau_R$, where τ_R is the cooling time $\tau_R = |L/T|^{-1}$. This provoked an understanding that short-wavelength perturbations always develop to create the condensation (isobaric) mode. Simple arguments implying that in the short-wavelength limit a perturbation is forced to relax to a state with homogeneous pressure distribution within the shortest, acoustic time $\tau_A = \lambda/c$, are usually invoked to motivate such a suggestion (Sasorov, 1988, Meerson, 1989). In the framework of this approach Meerson (1989) developed a technique to reduce hydrodynamical equations of a radiatively cooling gas in an 1D case to a more useful form similar to the Fisher–Kolmogorov–Petrovsky–Piskunov equation. Evidently, this reduced form is very promising for studying the dynamics of mass exchange between different phases of the ISG (Zeldovich and Pikelner, 1969, Doroshkevich and Zeldovich, 1981, McKee and Begelman, 1990) and pattern formation during the phase separation in a thermally unstable medium with constant pressure (Elphick *et al.*, 1991). However, this form has a restricted validity connected with a tendency of an arbitrary initial acoustic perturbation to break, in general, into two diverging waves which leave the region where they were originally located. In this paper we concentrate on the question as to how the dynamics of perturbations in a thermally unstable gaseous medium depends on the form of initial conditions. Thus, the aim of the paper is to outline a range of physical parameters and a class of initial conditions for which a reduced form of hydrodynamical equations corresponding to the isobaric approach is valid.

We present the basic equations and qualitative analysis of the problem in Section 2, and show typical numerical examples which clarify our arguments in Section 3. Section 4 contains a summary.

2 EQUATIONS AND QUALITATIVE ARGUMENTS

2.1 Basic Equations

The basic equations governing dynamics of a radiatively cooling gas were originally proposed by Field (1965):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0, \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}\right) + \frac{\partial P}{\partial x} = 0, \tag{3}$$

$$\frac{1}{\gamma - 1}\left(\frac{\partial P}{\partial t} + v\frac{\partial P}{\partial x}\right) + \frac{\gamma}{\gamma - 1}P\frac{\partial v}{\partial x} + \rho\mathcal{L}(\rho, T) - \frac{\partial}{\partial x}\left(\kappa\frac{\partial T}{\partial x}\right) = 0, \tag{4}$$

$$P - \frac{R}{\mu}\rho T = 0, \tag{5}$$

where κ is the thermal conductivity. For the sake of simplicity, we assume here implicitly the fractional ionizations of different coolants to be constants or given functions of temperature. Such an assumption allows us to omit additional equations of ionization equilibrium. The cooling rate $L(T)$ was accepted to reproduce qualitatively a conventional cooling rate of the ISG in the range $T = 30 - 10^4$ K, with two thermally stable parts at $T \sim 10^2$ K and $T \sim 10^4$ K, and quite flat, thermally unstable part in the intermediate range. For such cooling rate the effective equation of state $P(\rho)$ has two stable equilibrium points.

2.2 Arguments Based on Linear Theory

Solving the initial-value problem for the linearized equations (2)–(5) one can obtain the following equation for pressure perturbations (see Kryzhevsky and Shchekinov, 1995, hereafter KS for details)

$$\delta P = \frac{1}{2\pi i}\int\limits_{-i\infty+\sigma}^{+i\infty+\sigma} \frac{[p^2\delta P^0 - ikp\rho_0 c_0^2\delta v^0 - p_c c_0^2(p\delta\rho^0 - ik\rho_0\delta v^0)]}{(p-p_1)(p-p_2)(p-p_3)} e^{pt}\, dp,$$

where p_i are the roots of the characteristic equation for the linearized system (2)–(5), p_1 corresponds to the condensation mode, while $p_{2,3}$ to the acoustic ones (Field, 1965), $p_c = (\gamma - 1)\rho_0(\mathcal{L} - T_0\mathcal{L}_T/\rho_0)/c_0^2$ is the growth rate of the condensation mode in the short-wavelength limit (note that $|p_{2,3}| \sim kc_0 \gg p_c$ in this limit); subscript 0 refers to the unperturbed state, while superscript 0 denotes perturbations at the initial moment.

Let us consider for simplicity a particular case with $\delta v^0 = 0$. In this case the solution for the short-wavelength limit is

$$\begin{aligned}\delta P &= \frac{p_c^2}{p_2 p_3}(\delta P^0 - c_0^2\delta\rho^0)e^{p_c t} \\ &+ \frac{p_2\delta P^0 - p_c c_0^2\delta\rho^0}{p_2 - p_3}e^{p_2 t} + \frac{p_3\delta P^0 - p_c c_0^2\delta\rho^0}{p_3 - p_2}e^{p_3 t},\end{aligned}$$

where the limiting value $p_1 = p_c$ was aceepted. It is clearly seen from this equation that perturbations with $\delta P^0 = 0$ remain isobaric to within $\epsilon = p_c/kc_0 \ll 1$ at linear stages. At the same time, those perturbations which are far from being isobaric initially, $\delta P^0 \neq 0$, evolve to remain nonisobaric. Numerical studies demonstate that such a regime is also present at nonlinear evolutionary stages. This result is not unexpected. The short-wavelength limit, $\tau_A \ll \tau_{\dot{R}}$, implies that an arbitrary hydrodynamical perturbation tends to decay into diverging wave motions on the time scale sufficiently smaller than the time needed for this perturbation to feel effects connected with radiative energy losses. Moreover, in the limiting case $\tau_A/\tau_R = 0$ (which coincides with $\mathcal{L} \equiv 0$) radiative losses do not affect the dynamics of perturbations. Therefore, we can conclude from these qualitative arguments that in the short-wavelength limit perturbations of hydrodynamical variables can evolve to set in a condensation regime only for a special class of initial conditions corresponding exactly to isobaric perturbations.

3 NUMERICAL EXAMPLES

To illustrate this conclusion we show here two numerical models which follow the evolution of perturbations from initial linear state to final asymptotic behaviour being linear or nonlinear depending on the form of initial conditions. In numerical simulations, we used a code developed by Kovalenko (1996).

To make presentation more clear we use dimensionless variables with length, time and velocity normalized, respectively, by the initial size λ of a perturbation, the dynamical time $\tau_A = \lambda/c_0$ and the sound speed c_0; the initial perturbation is assumed to be localized; hydrodynamical variables ρ, P and T are normalized by their unperturbed values. In these units cooling time is equal to $\tau_R = \epsilon^{-1}$. The characteristic size of the perturbation λ was accepted to be larger than the Field length $\lambda_F \sim \sqrt{\kappa_0 T_0/\rho_0 L_0}$, which is a spatial scale on which radiative losses or external heating are in balance with the conductive heat exchange (Field, 1965; Begelman and McKee, 1990). In a thermally unstable medium, perturbations with $\lambda > \lambda_F$ evolve predominantly to grow, while those with $\lambda < \lambda_F$ predominantly decay.

Figures 1 and 2 demonstrate evolution of localized perturbations of two different types, namely isobaric (at the initial moment) perturbations in the first case (Figure 1), and acoustic ones in the second case (Figure 2). The unperturbed state of a system was assumed to be marginally stable with respect to the condensation mode,

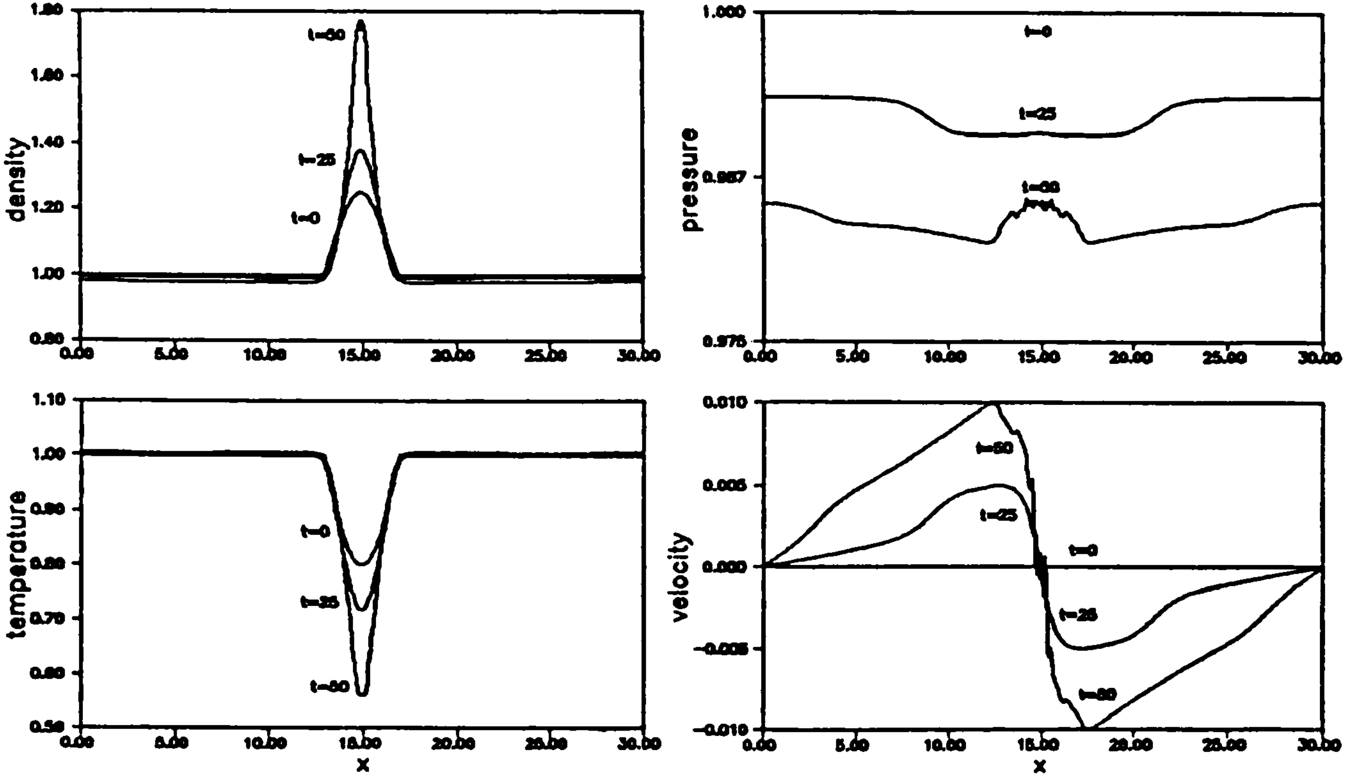

Figure 1 Evolution of an isobaric perturbation for $\epsilon = 0.1$ and $\lambda_F = 0.3\lambda$; the pressure, density, temperature and velocity profiles are presented at times equal to 0, 25, 50 of the dynamical time τ_A; $t = 0$ corresponds to the initial distribution. The initial perturbation has the amplitudes $\delta\rho^0/\rho^0 = 0.25$, $\delta T^0/T_0 = -0.2$ and $\delta v^0 = 0$.

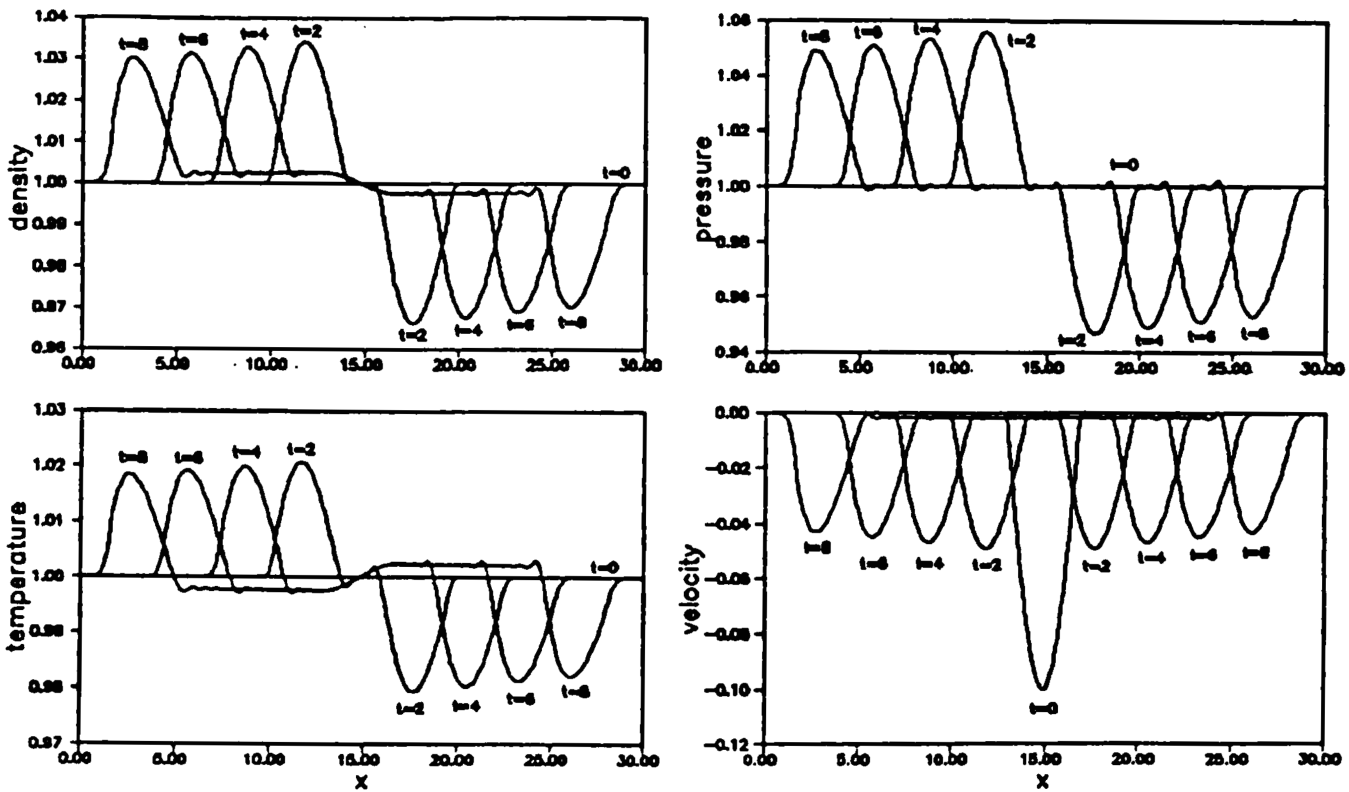

Figure 2 Evolution of acoustic perturbation for the same parameters as in Figure 1. The initial perturbation has the amplitudes $\delta P^0 = \delta\rho^0 = \delta T^0 = 0$, $\delta v^0 = 0.1$. The times shown are: 0, 2, 4, 6, 8.

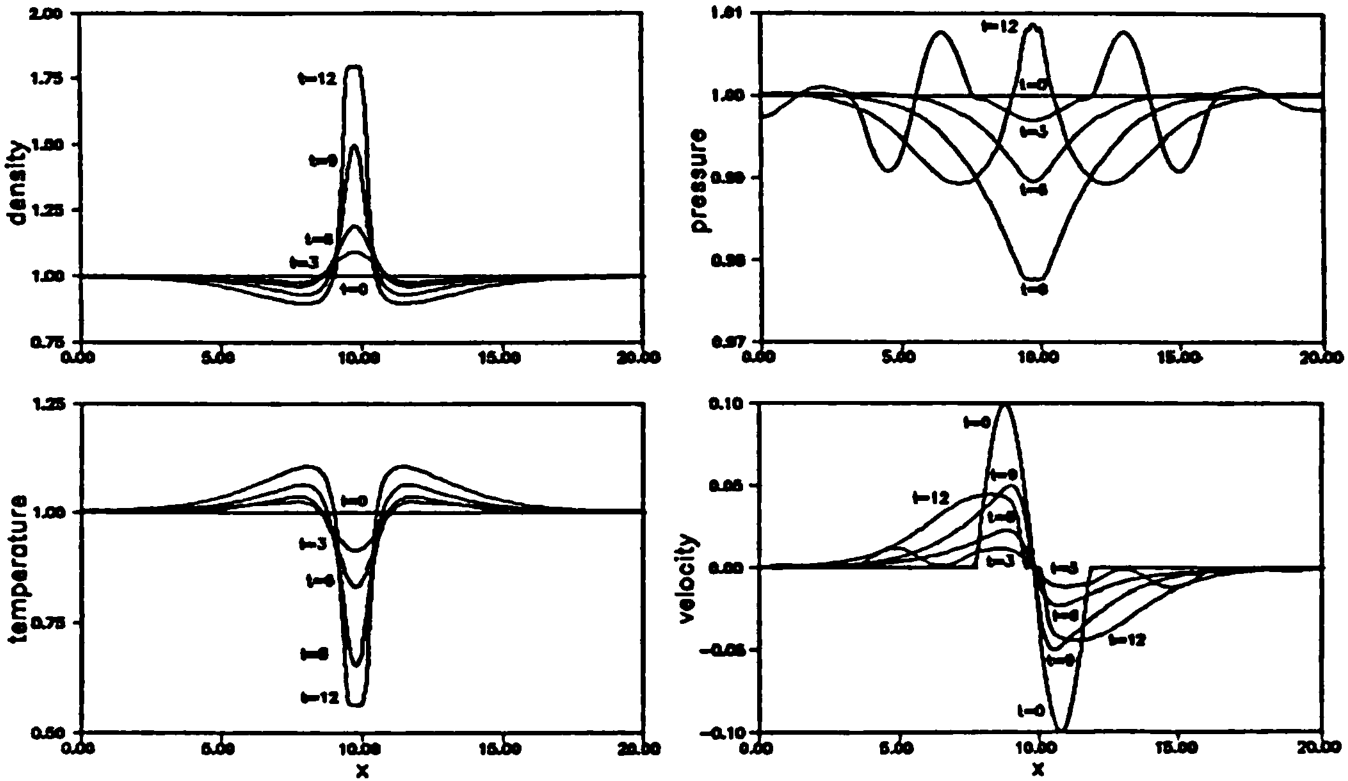

Figure 3 Evolution of acoustic perturbation in the case $\epsilon = 3$ and $\lambda_F = 0.3\lambda$. The initial perturbation has the amplitudes $\delta P^0 = \delta\rho^0 = \delta T^0 = 0$ and $\delta v^0 = 0.1$. The profiles are shown for the times 0, 3, 6, 9, 12.

which means that at this state $\mathcal{L}_\rho - T_0\mathcal{L}_T/\rho_0 = 0$. In other words, the unperturbed system was at the upper stable point on the effective equation of state $P = P(\rho)$ where $dP/dp = 0$, and therefore, positive $\delta\rho^0$ moves gas into the unstable region with $dP/d\rho < 0$. However, at the initial time the growth rate of linear perturbations is equal to zero, and thus even for sufficiently large initial amplitude the instability develops on a time scale larger than τ_R: in the particular case shown in Figure 1 it requires $\simeq 5\tau_R$.

Perturbations of the isobaric type (Figure 1) are readily seen to be unable to generate considerable pressure gradients and highly developed hydrodynamical motions: asymptotically, the characteristic velocity reaches the value $v = O(\epsilon)$ (KS). As a result, the perturbation remains localized near the region occupied initially.

Perturbations of the acoustic type (Figure 2), contrary to the isobaric ones $\delta v^0 \neq 0$, generate pressure gradient on the short (acoustic) time scale τ_A, which in turn initiates a decay of the initial perturbation into two diverging waves. Radiative losses lead in this case to a decrease in the amplitude of the perturbations since, in the short-wavelength limit, perturbations of acoustic (i.e., nonisobaric) type fade in linear theory (Field, 1965). At the same time, perturbations remain far from being evolved to the condensation (isobaric) mode. This is in accordance with qualitative considerations given above.

Perturbations of the acoustic type with comparable dynamical and radiative times $\tau_A \leq \tau_R$ evolve to develop the condensation (isobaric) mode contrary to the short-wavelength case. This is clearly seen in Figure 3 which shows a model with $\epsilon = 3$. This is in accordance with an expectation that in this case radiative losses are efficient to reduce an excess in pressure in the region occupied by the perturbed gas: the decrease of temperature and pressure due to radiative losses is estimated as

$$\frac{|\Delta P|}{P} \sim \frac{|\Delta T|}{T} \sim (\gamma - 1)\left(\frac{R}{\mu}\right)^{-1} \frac{L(T)}{T}\tau_A \sim 1.$$

As a consequence, an excess of pressure generated at the initial time by acoustic perturbation decreases, and thus the pressure equilibrium with surroundings sets in on the time scale $t \sim \tau_R$. In the particular case shown in Figure 3 after $t = 3$, pressure variations in the region occupied by the perturbed gas decrease from the initial amplitude $|\delta P^0/P_0| \sim 0.02$ to $|\delta P/P_0| \sim 0.005$.

Moreover, since this time scale τ_R is comparable with the dynamical one τ_A, the pressure excess does not propagate to neighbouring regions, resulting in the initial perturbation to remain localized.

4 CONCLUSIONS

Our results can be summarized as follows:

In the short-wavelength limit small perturbations in a radiatively cooling medium evolve in the isobaric regime only in those cases when they are isobaric from the very beginning.

If initial perturbations are of the acoustic type (e.g., $\delta v^0 \neq 0$, as shown in Figure 2) they decay and do not evolve to the isobaric regime. Note that numerical models with other types of acoustic perturbations ($\delta P^0, \delta\rho^0, \delta T \neq 0$) demonstrate a similar behavior (KS).

An important consequence for the theory of interstellar medium is that formation of interstellar clouds of small sizes is unlikely to be initiated by the condensation mode of thermal instability, since the this would require initial conditions of a special (isobaric) class. For the warm interstellar HI phase with temperature $T \sim 10^4$ K, number density $n \sim 0.1$ cm^{-3} and cooling rate $L(T) \sim 10^{-25}$ erg cm^3 s^{-1} (see Kaplan and Pikelner, 1979) the short-wavelength limit corresponds to $\lambda \ll 10^{20}$ cm. For a spherical contraction to a final state with temperature $T \sim 10^2$ K and number density $n \sim 10$ cm^{-3}, the short-wavelength limit would correspond to a cloud size of $R \ll 5 \times 10^{18}$ cm. Therefore, formation of diffuse clouds of small sizes $R < 1$ pc (see e.g. Knude, 1991) seems to be driven by mechanisms different from the thermal instability.

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References

Doroshkevich, A. G., and Zeldovich, Ya. B. (1981) Interfase between a hot and cold gas and the evolution of cold clouds in intergalactic space, *Zh. Eksp. Teor. Fiz.* **80**, 801–815 (*Soviet. Phys. JETP* **53**, 405).

Elphick, C., Regev, O., and Spiegel, E. A. (1991) Complexity from thermal instability, *Monthly Notic. Roy. Astron. Soc.* **250**, 617–628.

Field, G. B. (1965) *Thermal instability. Astrophys. J.* **142**, 531–567.

Field, G. B., Goldsmith, D. W., and Habing, H. J. (1969) Cosmic-ray heating of the interstellar gas, *Astrophys. J.* **155**, L149–154.

Kaplan, S. A. and Pikelner, S. B. (1979) Physics of the Interstellar Medium, Nauka, Moscow.

Knude, J. (1981) Diffuse interstellar clouds. Detectibility, distribution of diameters and column densities, *Astron. Astrophys.* **98**, 74–80.

Kovalenko, I. G. (1996) Superconservative difference scheme for gas dynamics, *J. Comput. Phys.*, to be submitted.

Kryzhevsky, A. B., and Shchekinov, Yu. A. (1995) Nonlinear response of a radiatively cooling gaseous medium to the form of initial linear perturbations, *Phys. Fluids*, to be submitted. (KS)

McKee, C. F. and Begelman, M. C. (1990) Steady evaporation and condensation of isolated clouds in hot plasma, *Astrophys. J.* **358**, 392–398.

Meerson, B. (1989) The nonlinear theory of thermal instability: the intermediate and short-wavelength limits, *Astrophys. J.* **347**, 1012–1020.

Pikelner, S. B. (1967) The ionization and heating of the interstellar gas by subcosmic rays. Clouds formation, *Astron. Zh.* **44**, 915–929 (1968, *Soviet. Astron.* **11**, 737).

Sasorov, P. V. (1988) On the emergence of structure through thermal instability, *Pisma Astron. Zh.* **14**, 306–310 (*Soviet. Astron. Lett.* **14**, 129–131).

Zeldovich, Ya.B. and Pikelner, S.B. (1969) The phase equilibrium and dynamics of a gas volume that is heated and cooled, *Zh. Eksp. Teor. Fiz* **56**, 310–315 (*Soviet. Phys. JETP* **29**, 170–173).