Publ. Astron. Soc. Japan 32, 623-627 (1980)

Chain-Reacting Thermal Instability in Interstellar CO Clouds

Yoshiaki SOFUE

Department of Astrophysics, Nagoya University, Chikusa-ku, Nagoya 464

and

Yutaka SABANO

Astronomical Institute, Tôhoku University, Sendai, Miyagi 980

(Received 1979 October 13; revised 1980 April 21)

Abstract

A new type of nonlinear, chain-reacting instability (CRI) is presented in which a sequential condensation occurs in a thermally unstable interstellar CO cloud, triggered by a local density perturbation. Model computation shows that the resulting condensations have a common spatial interval uniquely determined as $\lambda = 1.5 c_s \tau_e$, where c_s is the sound velocity of the unperturbed gas and τ_e the e-folding time of growth of linear thermal instability. The CRI mechanism could be related to the sequential star formation, unless other stabilizing effects, e.g., magnetic pressure, turbulence, or rotation are present.

Key words: CO clouds; Interstellar matter; Sequential star formation; Thermal instability.

1. *Introduction*

Sequential star formation in dense interstellar clouds has been demonstrated for some CO clouds associated with OB associations and H II regions (e.g. Elmegreen and Lada 1977; Woodward 1978). The star formation is considered to be triggered by the fragmentation of the clouds due to thermal and gravitational instabilities. The fragmentation process has been extensively studied both analytically and numerically [Elmegreen and Elmegreen (1978), Woodward (1978), and references cited therein]. In their earlier papers, Sabano and Kannari (1978) and Kannari et al. (1979) (these are hereafter referred to as Papers I and II) have shown that a nonsteady, contracting CO cloud fragments into small, denser clouds by thermal instability followed by a gravitational contraction. In the present paper we examine the influence of a local condensation in a thermally unstable CO cloud on its neighboring region with particular attention to a sequential formation of condensations.

The main aim of the present paper is to point out that a nonlinear effect of thermal instability brings about spatial propagation of disturbance in the context of an astronomical phenomenon. We, hence, intend to deal with a somewhat idealized model of interstellar CO cloud (see section 2) in order to clarify the new type of instability.

2. *Initial Condition*

The initial condition in the cloud is so chosen that the gas is in an unstable state at point A in figure 1. Such an unstable state may be realized in a gravitationally collapsing gas cloud, for example (Papers I and II). The time scale of the collapse is of the order of 10^7 yr at around point A–A_1, whereas the time scale of the thermal phenomenon discussed below is of the order of 10^6 yr, much smaller than the dynamical time scale. Here we neglect such a dynamical effect and simply regard the system to be in an unstable equilibrium state. Figure 1 shows a locus of the thermal and chemical equilibrium in the pressure–density diagram for the system with an optical depth of $\tau_v=1.5$. If a perturbation is given to the system, the gas proceeds either to point A_1 or to A_2, at which high-density condensations (A_2) are in pressure balance with the gas of low density (A_1). The density and temperature at point A are $n_0=510\,\mathrm{cm}^{-3}$ and $T_0=16\,\mathrm{K}$. Those in the low-density phase at A_1 are $n_1=250\,\mathrm{cm}^{-3}$ and $T_1=35\,\mathrm{K}$, and in the high-density phase A_2, $n_2=1300\,\mathrm{cm}^{-3}$ and $T_2=7\,\mathrm{K}$. The fractional abundance η of the available gaseous carbon in CO defined by $\eta=\xi(\mathrm{CO})/\xi(\mathrm{C})$ is approximately 0.2 at A, 0.06 at A_1, and 0.5 at A_2. Here $\xi(\mathrm{C})=7.3\times10^{-5}$ is the abundance of carbon relative to hydrogen in number, and $\xi(\mathrm{CO})$ is the fractional number density of CO molecules relative to the hydrogen number density $n=n(\mathrm{H})+2n(\mathrm{H_2})$ (see Paper II for detailes).

Instead of periodic perturbations as assumed in Papers I and II we give here a local density enhancement around $x=0$ in the gas. The amplitude is 10 percent of the background density in the form of $n=n_0+\Delta n$ with $\Delta n=0.1n_0\exp(-x^2/a^2)$, $a=0.03\,\mathrm{pc}$, and $n_0=510\,\mathrm{cm}^{-3}$. We assume that the cloud size is large enough compared with scale lengths of condensations so that the gas is regarded to be uniform, and no initial motion is given and no existence of magnetic field is assumed. We use the same computer program as used in Papers I and II in a one-dimensional and slab-symmetric case.

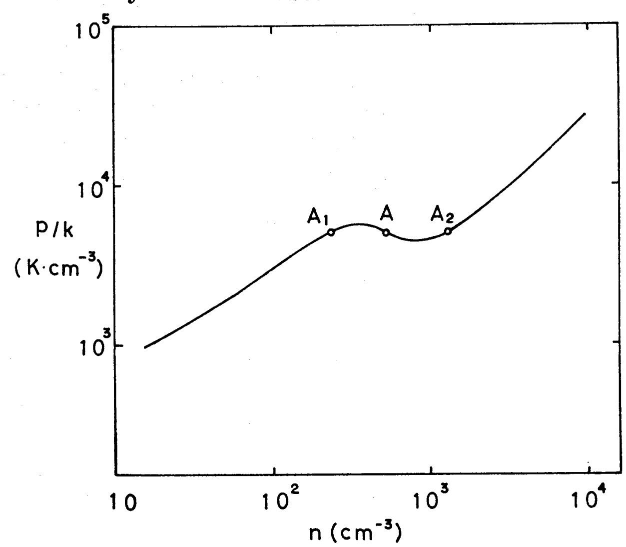

Fig. 1. Locus of the thermal and chemical equilibrium in the p/k–n diagram for a CO cloud gas, where p is the pressure, n the number density of hydrogen atoms, and k the Boltzmann constant. Point A represents the initial condition in an unperturbed gas for the present numerical computations (see the text).

3. *Chain-Reacting Thermal Instability*

Figure 2 shows the result of numerical computations. The density perturbation grows to a maximum density of $n_2=1300\,\mathrm{cm}^{-3}$ in a time scale of 0.6×10^6 yr. At the same time the gas in the neighboring region at $x=0.1$–0.2 pc shifts into a low-density phase of $n_1=200\,\mathrm{cm}^{-3}$. Since we assume a constant heating per particle by photons and cosmic rays (Paper I), the gas in the low-density region is relatively more heated so that the pressure therein becomes higher than the background pressure. Then because of the higher pressure the low-density gas pushes its neighboring gas toward increasing x to lead to a second density enhancement at $x=0.2$ pc. The second enhancement grows again into a high-density region with $n=n_2$ in a time scale of $\sim10^6$ yr, giving rise to the next low-density region at $x\approx0.3$ pc. In this way, the third, fourth, and many further condensations are produced in a sequential manner, i.e., a chain reaction of thermal

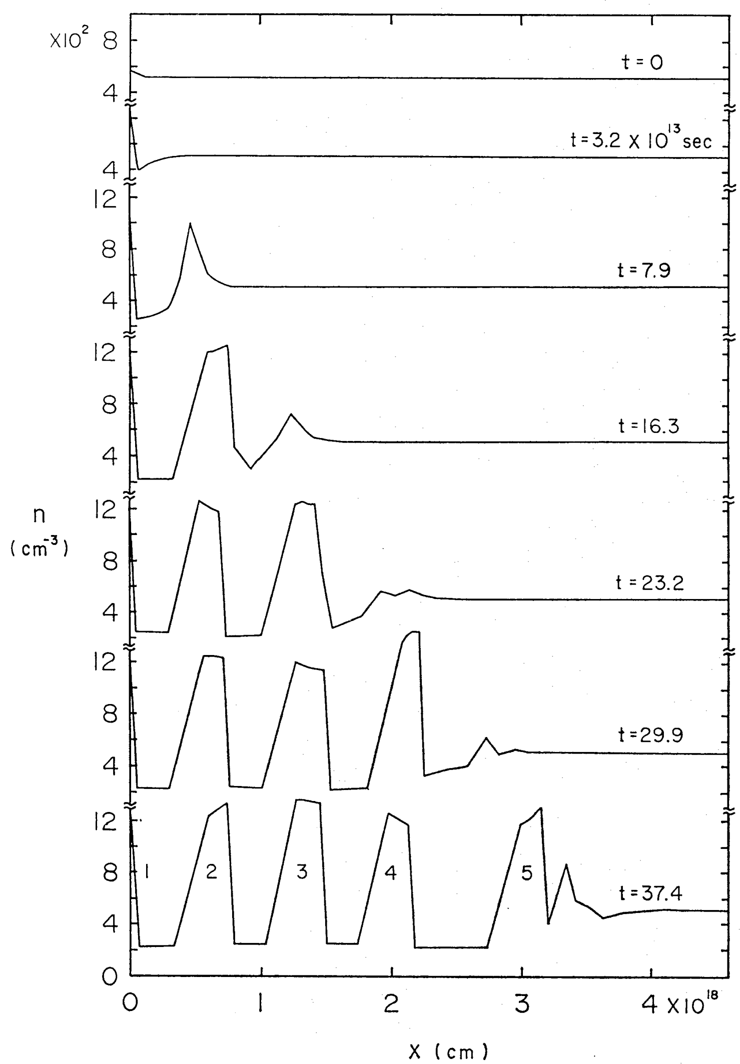

Fig. 2. Growth of a local density perturbation at $x=0$ followed by sequential nonlinear growth of neighboring condensations due to the chain-reacting instability (CRI). The background state of the gas is at point A in figure 1.

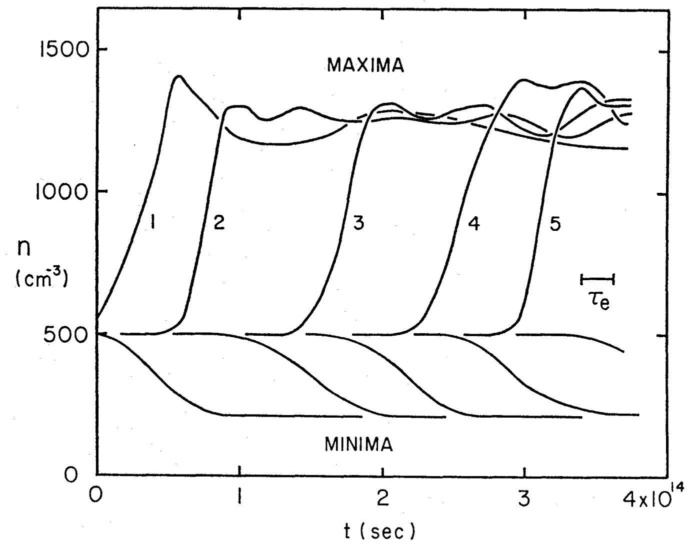

Fig. 3. Time variations of maximum densities in individual condensations 1 to 5 of figure 2 and intervening density minima.

instability takes place. The mean spatial interval between the neighboring condensations turns out to be $\lambda \cong 0.24$ pc regardless of their positions. Individual condensations have a common size of $l \cong 0.11$ pc.

Figure 3 shows time variations of individual density maxima and minima. Mean time interval from one condensation to the next to appear is approximately $\tau = 2.4 \times 10^6$ yr, which is 3.4 times the e-folding growth time τ_e of thermal instability given by the linear theory (e.g. Field 1965), $\tau_e = 0.7 \times 10^6$ yr (Paper I). The sound velocity of the background gas is $c_s = 0.24$ km s^{-1}, and the expected minimum spacing of condensations from the linear theory is about $\lambda_{min} = c_s \tau_e = 0.16$ pc. The computed spacing of 0.24 pc is somewhat larger than this value, $\lambda \cong 1.5 c_s \tau_e$, and the scale size of the condensation is given by $l = 0.69 c_s \tau_e$. These relations are not affected by the form of the initial density perturbation, provided the scale length a small compared with $c_s \tau_e$; the spacings and sizes of the condensations are thus uniquely determined by the characteristic parameters c_s and τ_e of the background gas alone. The front of the sequential condensation appears to propagate at a speed of $\lambda/\tau \cong 0.10$ km s$^{-1} \cong 0.42 c_s$.

4. *Discussion*

The present chain-reacting instability (CRI) acts so that a thermally unstable system of gas evolves into many periodically sliced high-density condensations sandwiched between low-density gases in a sequential manner triggered by a local perturbation. Namely a signal can propagate into an unstable medium at about half the sound speed, leaving in its wake a sequence of stable condensations. Such a mechanism could be related to a sequential star formation in interstellar CO clouds, if the condensations evolve further into star formation sites. It is conjectured that the CRI propagates not only in the x-direction but also in directions perpendicular to it. Then the system will evolve into many fragments of spacing $\sim \lambda$, each of which has mass of the order of $M \sim \rho_0 \lambda^3 \sim 0.2 M_\odot$ with $\rho_0 = m_H n_0$, where m_H the mass of hydrogen atom. The spacing and size of the fragments are much smaller than those of OB associations and H II regions ($\sim$10 pc). The present mechanism would therefore be not directly related to these objects but to some smaller-scale sequential condensations probably related to the formation of less-massive stars. For more detailed discussion of such a fragmentation, we need a nonlinear and three-dimensional analysis of the CRI, which is beyond the scope of the present paper. We also have to consider other stabilizing effects which are neglected in the present investigation, such as magnetic pressure, turbulence, etc., in order to understand the real situation.

We stress that this kind of sequential growth of a local perturbation is a result characteristic of a nonlinear treatment of thermal instability. The CRI mechanism is predicted neither from linear theories nor from the gravitational instability. The CRI is common to any thermally unstable system. In fact, according to our further computations for the formation of cold H I clouds from a warm intercloud gas in a thermally unstable state, the CRI takes place in a similar manner to the CO cloud case. The resulting mean spacing of the H I condensations is 17 pc and the time interval from one to the next to appear is 10^7 yr. Since the minimum wavelength expected from the linear theory is $c_s\tau_e \cong 10$ pc, we have $\lambda \cong 1.7 c_s\tau_e$ in this case.

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