SEQUENTIAL STAR FORMATION IN TAURUS
MOLECULAR CLOUD 1

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We discuss the fragmentation of a filamentary cloud on the basis of a 1-dimensional hydrodynamical simulation of a self-gravitating gas cloud. The simulation shows that dense cores are produced with a semi-regular interval in space and time from one edge to the other. At the initial stage the gas near one of the edges is attracted inwards by gravity and the accumulation of the gas makes a dense core near the edge. When the dense core grows in mass up to a certain amount, it gathers gas from the other direction. Accordingly the dense core becomes isolated from the main cloud and the parent filamentary cloud has a new edge. This cycle repeats and the fragmentation process propagates towards the other edge. The propagation speed is a few tens of percent larger than the sound speed. According to the theory, the age difference for the northwest-most and southeast-most cores in TMC-1 is estimated to be 0.68 pc/0.6 km s\(^{-1}\) = 10\(^6\) y. The estimated age difference is consistent with that obtained from the chemical chronology.

*Subject headings:* hydrodyanamics,instabilities,ISM: individual objects: Taurus Molecular Cloud 1.
1. INTRODUCTION

The star formation process seems to propagate by several mechanisms on both large and small scales (see, e.g., a review by Elmegreen 1992). A classical example of propagating star formation is the linear sequences of stellar subgroups in Orion OB associations (Blaauw 1964). A larger scale example is the super giant shell in the Large Magellanic Cloud (Westerlund & Mathewson 1966). The shell consists of HI clouds and bright blue stars, and surrounds two supernova remnants and stellar associations. Similar shells are also seen in our Galaxy. In these examples, massive stars trigger star formation in the neighborhood through supernova explosion and UV radiation.

The star formation process may also propagate in a dark cloud. Recently Hirahara et al. (1992) have found that dense cores are successively formed. According to them, a filamentary cloud, Taurus Molecular Cloud 1 (TMC-1) is elongated in the NW-SE direction and contains five dense cores called A-E from NW to SE. The cores have different chemical ages and are older in NW than in SE. The age difference is of the order of $10^6$ y. This indicates propagation of dense core formation.

If cores A - E are formed successively, it is likely that a causal mechanism works there. However it could be neither supernova explosion nor UV radiation from young stars; no influential stars are found in the vicinity of TMC-1. Although various models are proposed for sequential star formation on large and small scales, most of them invoke young massive stars. They cannot be applied to TMC-1.

In this paper we propose a new mechanism for sequential core (star) formation which operates in a filamentary molecular cloud. In our model, formation of a dense core triggers that of another core. Once a core is formed, the gravitational field is changed and accordingly the gas flows. Another core is produced by the gas flow and the cycle repeats.
Using a 1-dimensional (1D) hydrodynamical model we demonstrate how this mechanism works.

In section 2 we construct a 1D model for the dynamics of a filamentary cloud. Some characteristics of the 1D model are investigated analytically. It is shown that the 1D model can explain the fragmentation of a filamentary cloud due to the self-gravity of the gas. Numerical simulations of the 1D model are shown in section 3. They demonstrate that cores are produced sequentially with semi-regular temporal and spatial intervals in a filamentary cloud. The apparent propagation speed of fragmentation is somewhat larger than the effective sound speed. In section 4 we summarize observations so far reported for TMC-1 and apply our model to TMC-1. The apparent propagation speed of fragmentation in TMC-1 is of the order of the turbulent velocity. Since the filament length and velocity dispersion are 0.68 pc and 0.6 km s$^{-1}$ in TMC-1, the time scale for the propagation of fragmentation is estimated to be $10^6$ yr. This estimate is consistent with the age of cores calculated from their chemical abundances. In section 5 we discuss the dynamical and chemical evolution of a filamentary cloud during fragmentation.

2. 1-DIMENSIONAL MODEL

2.1. Model Equations

When a filamentary cloud fragments, the gas motion is mainly in the direction parallel to the filament axis. Thus, we approximate the gas motion to be 1-dimensional. The equation of motion and the equation of continuity are expressed as

$$\rho \left( \frac{\partial v}{\partial t} + \frac{v}{\partial z} \right) + \frac{\partial P}{\partial z} + \rho \frac{\partial \psi}{\partial z} = 0 ,$$

(1)
and
\[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z} (\rho v) = 0, \] respectively, where \( v, \rho, P, \) and \( \psi \) are the velocity along the filament axis, the density, the pressure, and the gravitational potential, respectively. The Poisson equation is arranged to be
\[ \frac{\partial^2 \psi}{\partial z^2} - \frac{\psi}{R^2} = 4\pi G \rho, \] where \( G \) and \( R \) are the gravitational constant and a length scale for the filament radius. The derivative in the radial direction in the Poisson equation is replaced with a constant coefficient \([ the \ second \ term \ in \ the \ left \ hand \ side \ of \ equation \ (3) ]\). Equations (1) thorough (3) denote the gas motion in a filamentary cloud under the 1-dimensional approximation.

2.2. The Filamentary Cloud Model and Its Stability

In this subsection we discuss a model for a infinitely long \((\partial/\partial z = 0)\) filamentary cloud and its stability. A steady state solution of equations (1), (2), and (3) is expressed as
\[ \rho(z) = \rho_0 = \text{const.} \] (4)
\[ v(z) = 0, \] (5)
and
\[ \psi(z) = -4\pi G \rho_0 R^2. \] (6)
We consider a small perturbation around this equilibrium. The density perturbation is assumed to be in the form of
\[ \rho(z, t) = \rho_0 + \rho_1 \exp (ikz + i\omega t). \] (7)
Then the dispersion relation is expressed as

$$\omega^2 = -4\pi G\rho_0 \frac{k^2 R^2}{1 + k^2 R^2} + c_s^2 k^2. \quad (8)$$

Equation (8) is qualitatively similar to the approximate dispersion relation for a filamentary cloud (Hanawa et al. 1993),

$$\omega^2 = -4\pi G\rho_c \frac{kH}{1 + kH} + c_s^2 k^2, \quad (9)$$

where the equilibrium density distribution is assumed to be

$$\rho_0 = \rho_c (1 + r^2/8H^2)^{-2}. \quad (10)$$

This similarity justifies our 1D approximation and suggests $R \simeq H$.

In our 1D approximation, the model is unstable whenever

$$4\pi G\rho_0 R^2 > c_s^2. \quad (11)$$

We think that inequality (11) is satisfied in a gravitationally bound filamentary cloud. For a 2-dimensional model of a filamentary cloud there is a condition of magnetohydrodynamical equilibrium in the radial direction;

$$4\pi G\rho_c H^2 = c_s^2 + 2\Omega_c^2 H^2 + \frac{B_c^2}{16\pi \rho_c} (1 + \cos^2 \theta), \quad (12)$$

where $\Omega_c$, $B_c$ and $\theta$ denote the angular velocity at the filament center, the magnetic field density at the center, and the pitch angle of the magnetic fields at $r = \infty$ (see Hanawa et al. 1993 for further details). Equation (12) means that the gravitational force should be equated with the sum of the thermal and magnetic pressures and the centrifugal force.

If a filamentary cloud is permeated with magnetic fields and/or rotates around the axis, inequality (11) is fulfilled. For example, TMC-1 has velocity gradient along the minor axis which can be ascribed to rotation around the major axis (e.g., Olano, Walmsley & Wilson 1988). In the following we assume inequality (11) except when otherwise stated.
The growth rate and wave number of the most unstable mode are derived to be

\[ (-i\omega)_{max} = \sqrt{4\pi G \rho_0 - c_s/R}, \]  

(13)

and

\[ k_{max} = \frac{1}{R} \sqrt{\frac{R\sqrt{4\pi G \rho_0}}{c_s} - 1}, \]  

(14)

from equation (8). The values of \((-i\omega)_{max}, k_{max},\) and \(\lambda \equiv 2\pi/k_{max}\) are summarized in Table 1. Equations (13) and (14) are used to interpret the 1D nonlinear simulation of fragmentation.

### 2.3. Periodically Distributed Cores

Equations (1) - (3) have a more general steady state solution where the density changes periodically. In hydrostatic equilibrium the density is expressed as

\[ \rho(z) = \rho(0) \exp \left\{ -\frac{\psi(z) - \psi(0)}{c_s^2} \right\}. \]  

(15)

Substituting equation (15) into equation (3) we obtain

\[ \frac{d^2\psi}{dz^2} - \frac{\psi}{R^2} = 4\pi G \rho(0) \exp \left\{ -\frac{\psi(z) - \psi(0)}{c_s^2} \right\}. \]  

(16)

In the following we assume that the density has the minimum value, \(\rho(0) = \rho_{\text{min}}\) at \(z = 0\), and hence the gravitational potential is the highest at \(z = 0\), with \(\psi(0) = \psi_{\text{max}}\). Integrating equation (16) multiplied by \(d\psi/dz\) we obtain

\[ \left| \frac{d\psi}{dz}(z) \right|^2 = \left| \frac{\psi(z)}{R} \right|^2 - \left| \frac{\psi(0)}{R} \right|^2 - 8\pi G \rho(0) c_s^2 \left\{ \exp\left(-\frac{\psi(z) - \psi(0)}{c_s^2}\right) - 1 \right\}. \]  

(17)
Since $d\psi/dz$ is expressed as a function of $\psi$, we can obtain $z$ as a function of $\psi$ for given $\rho(0)$ and $\psi(0)$ which satisfy

$$-4\pi G\rho(0)R^2 \leq \psi(0) < 0.$$  

(18)

When $\psi(0) = -4\pi G\rho(0)R^2$, the density and gravitational potentials are spatially constant.

3. NUMERICAL SIMULATION

3.1. Numerical Methods

The differential equations (1) - (3) are integrated numerically in Lagrangian coordinates with a fully implicit scheme. We introduce a Lagrangian coordinate, $s$, defined by

$$ds = \rho(z) \, dz.$$  

(19)

Using $s$ we rewrite equations (1) - (3) into

$$\left(\frac{dz}{dt}\right)_s = v,$$  

(20)

$$\left(\frac{dv}{dt}\right)_s = -\frac{1}{\rho_c} \left(\frac{\partial P}{\partial s}\right) - g,$$  

(21)

$$P = c_s^2 \rho,$$  

(22)

$$\rho = \rho_c \left(\frac{dz}{ds}\right)^{-1},$$  

(23)

$$\frac{\partial g}{\partial s} = \frac{\rho_c \psi}{\rho R^2} + 4\pi G\rho_c,$$  

(24)

$$\frac{\partial \psi}{\partial s} = \left(\frac{\rho_c}{\rho}\right) g.$$  

(25)

We followed the time evolution of a Lagrangian mesh point, $z_i (0 \leq i \leq n)$ using the difference equations,

$$z_j = z_j^{(\text{old})} + \Delta t \, v_j,$$  

(26)
\[ v_j = v_j^{(\text{old})} + \Delta t \left( -c_s^2 \frac{\rho_{j+1/2} - \rho_{j-1/2}}{\rho_c \Delta s} - g_j \right), \]  

(27)

where

\[ \rho_{j+1/2} = \rho_c \left( \frac{z_{j+1} - z_j}{\Delta s} \right)^{-1}, \]

(28)

\[ \psi_{j+1/2} = \frac{\rho_{j+1/2} R^2}{\rho_c} \frac{g_{j+1} - g_j}{\Delta s} - 4\pi G \rho_{j+1/2} R^2, \]

(29)

\[ g_j = \frac{\rho_{j+1/2} + \rho_{j-1/2}}{2\rho_c} \frac{\psi_{j+1/2} - \psi_{j-1/2}}{\Delta s}. \]

(30)

We take the fixed boundary condition,

\[ z_0 = \text{const. and } z_n = \text{const.}, \]

(31)

at the both ends. The number of the Lagrangian mesh points is \( n = 1.1 \times 10^4 \) in most of numerical simulations shown in this paper. The time step is taken to be \( \Delta t = 5.0 \times 10^{-3} \).

In the following we take units of \( R = 1, \rho_0 = 1, \) and \( 2\pi G \rho_0 = 1 \) except when otherwise stated.

### 3.2. Standard Model (Model 1)

As a typical example we describe model 1 where the sound speed is taken to be \( c_s = 1.0 \). The initial gas distribution is assumed to be

\[ \rho = 0.1 \rho_0 \quad \text{for } -50 \leq z \leq 0 \]

(32)

\[ = 1.0 \rho_0 \quad \text{for } 0 < z \leq 50 \]

(33)
The time evolution of model 1 is shown in figure 1 with grey scale representation. The abscissa and ordinate are the $z$-coordinate and time, respectively.

At an early stage with $t \approx 2$, the gas near the left edge of the cloud is attracted by the cloud gravity and flows to right. A dense core is produced near $z \sim 4$ at $t \approx 4$. The maximum density at $t = 6$ is $\rho = 3.574$ at $z = 5.433$. The core is in a quasi-static equilibrium after $t \geq 8$. As the core grows in mass, it attracts gas also from its left side. The first core becomes isolated from the main cloud at $t \approx 10$ and the cloud has a new edge.

The second core is produced in a similar way at $t \approx 12$. Cores are produced sequentially with a time interval of $\Delta t \approx 8$ and spatial interval of $\Delta z \approx 9$. The spatial interval is nearly equal to the wavelength of the fastest growing mode in this model ($\lambda_{max} = 9.763$). The apparent propagation speed of fragmentation, $v_{frag} \equiv \Delta z/\Delta t \approx 1.1$, is a little faster than the sound speed. Nakamura, Hanawa & Nakano (1993) estimated the propagation speed to be

$$v_{frag} = \sqrt{2\omega(k_{max})\frac{\partial^2 \omega}{\partial k^2}}_{k=k_{max}},$$

from a linear stability analysis (see their Appendix 4). Substituting equations (13) and (14) into equation (35) we obtain

$$v_{frag} = \left(10 - \frac{6R\sqrt{4\pi G\rho}}{c_s}\right)^{1/2}c_s.$$  

Equation (36) gives a good estimate, $v_{frag} = 1.23c_s$ for model 1.

Figure 2 shows the density and velocity distribution at $t = 20$. The density profile has peaks at $z = 9.00, 15.73, \text{ and } 23.30$, where the peak density is $18.06, 9.19, \text{ and } 2.60$, respectively. The first and second cores are in a quasi-static state and the velocity is almost
constant in each core. These cores accrete gas from both sides and standing shock waves are formed at the core surfaces. The formation of the third core is in progress. The first and second cores attract each other and merge into a single core at a later stage. This means that the periodic distribution of gas discussed in subsection 2.3 is also unstable against merging.

The exact epoch of merging depends on the details of the initial density distribution and even on the number of the mesh points. Although a trial computation with fewer mesh points is quite similar to model 1 in the early stage, the first and second cores merge earlier in the trial computation. This is because fewer mesh points give a larger amplitude of numerical noise. Compare model 1 with models 4 and 5 for the dependence on the initial density distribution.

3.3. Dependence on $c_s$

In order to study the dependence on $c_s$ we constructed models 2 and 3 where the sound speed is taken to be $c_s = 1.1$ and 1.2, respectively. The initial density distribution of models 2 and 3 is the same as that of model 1.

The time evolution of models 2 and 3 are shown in figures 2 and 3, respectively. Models 2 and 3 are qualitatively similar to model 1. The spatial interval between cores is $\Delta z \simeq 10$ and $\simeq 12$ for models 2 and 3, respectively. The propagation speed of fragmentation is $v_{frag} \simeq 1.2$ and 1.4 for models 2 and 3, respectively. When $c_s$ is larger, the cores are wider in separation and fragmentation propagates faster. These relations qualitatively agree with equations (14) and (36).
3.4. Dependence on Initial Density Distribution

We constructed models 4 through 7 to study the dependence on the initial density distribution. The initial density profile has a sharp edge at $z = 0$ in models 1, 2, and 3. The sharp edge is introduced for making a model which is as simple as possible and unlikely to be realized in interstellar space. In models 4 through 7 the initial density increases from 0.1 to 1.0 with a constant density gradient $(d\rho/dz)$ in the region $-a \leq z \leq a$ where $a$ is taken to be $a = 2.5, 5, 20, \text{ and } 50$ in models 4, 5, 6, and 7, respectively. The sound speed is taken to be $c_s = 1.0$ in models 4 through 7. Figures 5, 6, 7, and 8 show the time evolution of models 4, 5, 6, and 7, respectively. Sequential fragmentation also takes place in models 4 through 7.

Model 4 is not much different from model 1. A major difference between them is the distance between the first and second cores at $t = 24$. It is shorter in model 1 than in model 4. A small difference in an early stage is amplified by merging instability.

Model 5 is also similar to models 1 and 4 except that formation of the first core is delayed by $\Delta t \simeq 2$ and shifted to the right by $\Delta z \simeq 3$ in model 5. The delay is due to the low density gradient at the initial stage and the shift is because the effective edge is shifted to the right in model 5. Model 5 is qualitatively similar also in the formation of the second and third cores to models 1 and 4. A sharp edge at the initial stage is not essential for the propagation of fragmentation.

Model 6 shows also the propagation of fragmentation. In model 6 cores are formed both to the left and right of the first core. Propagation to the left is slower than that to the right. This is because the mean density is lower and the self-gravity is weaker in the left of the first core. Propagation to the right terminates at $t \simeq 28$ when it reaches to $z = 50$, the boundary of computation. Propagation to the left will terminate after it reaches to a
less dense region (see also figure 6).

In model 7 the initial density increases from 0.1 to 1 in the region \(-50 \leq z \leq 50\). The first core is formed at \(z = 50\) where the initial is the maximum. Since the reflection boundary is assumed at \(z = 50\), fragmentation propagates both to the left and right from \(z = 50\) although only propagation to the left is shown in figure 8.

As seen models 4 through 7 propagation of fragmentation is ubiquitous in the gravitational instability of a long filamentary cloud. Once a core is formed, subsequent cores are formed in general on the left and right sides. When the first core is formed near the edge of a cloud, propagation to the diffuse side diminishes (see figure 6). The first core may often be formed near an edge of a filamentary cloud since the large density gradient thereof triggers formation of the first core. In such a case cores are formed from an edge to the other in a long filamentary cloud.

3.5. Comparison with 2D Simulation

Bastien (1983) followed the non-linear fragmentation of a non-rotating non-magnetized cylindrical cloud with a 2D hydrodynamical code for the first time. The numerical simulation was extended by Rouleau & Bastien (1990), Bastien et al. (1992), and Arcoragi et al. (1992). They followed the collapse and fragmentation of an initially uniform cylindrical cloud having density, \(\rho_0\), diameter, \(D\), and length \(L\).

The qualitative features of their simulation depend mainly on \(J_0\), the ratio of the gravitational to the thermal energies. When \(J_0 > J_c\), the cloud is not massive enough to be gravitationally bound. When \(J_0 > J_{\text{spindle}}\), the cloud collapses as a whole into a thin needle and does not fragment. The case of \(J_c < J_0 < J_{\text{spindle}}\) corresponds to our 1D simulation which implicitly assumes hydrostatic balance in the radial direction. When
\( J_c < J_0 < J_{\text{spindle}} \), two condensations are formed on the axis. They are symmetric with respect to the cloud center and move toward the center while their density increases. They collide with each other at the center when \( J_0 \) is close to \( J_c \). The whole cloud becomes a thin needle when \( J_0 \) is relatively large.

Our simulation is qualitatively similar to their simulations up to the formation of the two condensations, one of which is the mirror image of the other. A condensation is produced near the cloud edge in both simulations as far as we know from the published figures. Further evolution is, however, very different between their simulations and ours. Second generation condensations are not formed in their simulation. The difference comes mainly from the fact that the hydrodynamical equilibrium in the radial direction can be realized only with difficulty for an isothermal non-magnetized gas. Only when the mass per unit length has a certain value (\( = 2c_s^2/G \)) can an isothermal non-magnetized cylindrical cloud be in equilibrium. The difference may in part be due to the numerical scheme. It is difficult for an explicit code to follow further evolution after the formation of high density cores. Low spatial resolution may induce the coalescence of high density condensations at an earlier stage. We think that condensations are formed successively on the axis in a 2D numerical simulation if the initial cloud is in a quasi-static equilibrium and the numerical code can follow the long term evolution.

### 4. APPLICATION TO TMC-1

In this section we briefly summarize the observations of TMC-1 with emphasis on its star formation history.

Taurus Molecular Cloud 1 (TMC-1) is one of filamentary clouds in the Taurus dark cloud complex, whose distance from the Sun is about 140 pc (Elias 1978). The filamentary
structure of this cloud was first recognized by Little and his collaborators (1978) through mapping observations of HC$_5$N. Since then TMC-1 has been extensively studied using various molecular lines such as NH$_3$, CS, HC$_3$N and HC$_7$N (Tölle et al. 1981; Snell, Langer, & Frerking 1982; Olano, Walmsley & Wilson 1988). It is now established that the filament is extended from SE to NW with an apparent size of 17′ × 2′, which corresponds to a linear size of 0.68 × 0.08 pc (Hirahara et al. 1992; Olano, Walmsley & Wilson 1988). A significant velocity gradient (3.8 km s$^{-1}$ pc$^{-1}$) is observed along the minor axis (Olano et al. 1988). Such a velocity structure is interpreted as possible rotation or overlapping of several filaments. The global magnetic field in this region was studied by Moneti et al. (1984). They carried out optical and infrared polarimetry in this region, and found that the magnetic field direction is from SW to NE, being perpendicular to the filament.

This source has also been a good target for detailed studies on chemistry in dark clouds, since a number of molecular species are detected. Little et al. (1979) first pointed out that a large chemical gradient is seen along the major axis of the filament. They observed the NH$_3$ and HC$_3$N lines, and found that NH$_3$ is intense in the NW part whereas HC$_3$N is intense in the SE part. However the origin of such a chemical gradient has long been a puzzle.

Hirahara et al. (1992) mapped TMC-1 using the CCS lines with a spatial resolution of 40″. Since the optical depths of the spectral lines of CCS are not very high, these lines are suitable for detailed studies on the structure and chemistry of the cloud. They reported that TMC-1 is not a uniform filament but a chain of several dense cores spaced almost regularly (the left panel of Figure 9). Five cores are identified, each of which has a diameter of 0.04 - 0.10 pc. These cores can also be seen in the NH$_3$ map (the right panel of Figure 9). They measured the cloud density accurately by observing the optically thin emission of the C$^{34}$S ($J = 1 - 0$ and $J = 2 - 1$) lines, and found that the density tends to increase from
SE to NW. The density averaged over the 40″ beam is $4 \times 10^4 \text{ cm}^{-3}$ at the cyanopolyyne peak (Core D), whereas it is $4 \times 10^5 \text{ cm}^{-3}$ at the NH$_3$ peak (Core B). The size and density of each core are comparable to typical values for dense cores reported by Benson & Myers (1989).

From these results, the chemical gradient seen in TMC-1 is ascribed to a systematic chemical difference among the dense cores. Hirahara et al. (1992) suggested that the chemical difference originates from the core age. According to gas-phase chemical model calculations (Millar & Herbst 1990; Suzuki et al. 1992), carbon-chain molecules like CCS are abundant in the early stages of cloud evolution, while NH$_3$ is only abundant in the late stages. On the basis of this model, the NW cores are considered to be older than the SE cores. In fact, the density tends to be higher in the NW core. Furthermore, the IRAS source (04381+2540) exists near the NW core, indicating that star-formation has already taken place.

The chemical lifetime of carbon-chain molecules is about $10^6 \text{ yr}$ according to chemical model calculations (Leung, Herbst & Huebner 1984; Tarafdar et al. 1985; Suzuki et al. 1992). This time scale is mainly related to the conversion time scale from C to CO. When a cloud is in a diffuse stage with $A_V < 2$, the major forms of carbon are C$^+$ and C, because molecules are mostly photodissociated by the interstellar ultraviolet radiation. As the cloud becomes opaque due to gravitational contraction, photodissociation becomes ineffective, and hence, C$^+$ and C are consumed to form a stable molecule, CO, through various chemical reactions. The conversion time scale from C to CO in the opaque region is inversely proportional to the cosmic ray ionization rate and almost independent of the cloud density. Because a high abundance of C$^+$ and C is essential to the production of carbon-chain molecules, carbon-chain molecules can only exist in the early stages of cloud evolution. The lifetime of carbon-chain molecules is almost comparable to the production
time scale of NH$_3$. Therefore, the abundance ratio between carbon-chain molecules and NH$_3$ is a good indicator of evolutionary stages during the 10$^6$ yr after the cloud becomes opaque.

On the basis of the above scenario on chemical evolution, the age difference between the cyanopolyyne peak position and the NH$_3$ peak position in TMC-1 is expected to be about 10$^6$ yr, i.e., the cores in TMC-1 are successively formed within this time scale. On the other hand, our model simulation suggests that the propagation speed of core formation is slightly larger than the effective sound speed. The velocity width observed in TMC-1 is 0.4 - 0.8 km s$^{-1}$, depending on the position. When we adopt 0.6 km s$^{-1}$ as the effective sound speed, the difference in ages between the cyanopolyyne peak and NH$_3$ peak is estimated to be 7 $\times$ 10$^5$ yr. This value is almost consistent with the time scale estimated from the chemical differences. These results further support the prediction that the cores in TMC-1 are successively formed from NW to SE.

5. PHYSICAL AND CHEMICAL EVOLUTION OF CORES

Thus far, TMC-1 is unique as a filamentary cloud indicating sequential core formation. Our mechanism for the sequential core formation, however, seems to work in a filamentary molecular cloud. The uniqueness of TMC-1 may be solely due to the fact that TMC-1 has been observed extensively in various molecular emission lines. In this section we discuss guidelines for searching for filamentary clouds which may contain cores with different ages.

As discussed in the previous section, the chemical evolution begins as a result of the UV shielding due to fragmentation and contraction. Let us suppose that the visual extinction is $A_v \simeq 3$ at the onset of the chemical evolution. This means that the penetration of UV radiation to the core is reduced by a factor of a thousand at the onset. Since the visual
extinction is well correlated with the integrated intensity of a molecular emission line, we can estimate the brightness of a core at the onset of the chemical evolution. Cernicharo & Guélin (1987) evaluated the correlation between the visual extinction and the integrated intensities of $^{12}$CO, $^{13}$CO, and C$^{18}$O to be

$$ I(^{12}\text{CO}) = 5.0 \pm 0.5 \cdot (A_V - 0.5 \pm 0.2) \text{K km s}^{-1}, \quad (37) $$

$$ I(^{13}\text{CO}) = 1.4 \pm 0.2 \cdot (A_V - 0.7 \pm 0.3) \text{K km s}^{-1}, \quad (38) $$

and

$$ I(\text{C}^{18}\text{O}) = 0.28 \pm 0.5 \cdot (A_V - 1.5 \pm 0.3) \text{K km s}^{-1}, \quad (39) $$

for the Taurus region. The core of $A_v = 3$ is already opaque for $^{12}$CO, semi-transparent for $^{13}$CO and transparent for C$^{18}$O. This means that the decay of CCS and production of NH$_3$ take place in a dense core seen in the C$^{18}$O map.

A core which can be identified in a C$^{18}$O map is thought to have the a density $\gtrsim 3 \times 10^4$ cm$^{-3}$. The dynamical time scale of such a dense core is short,

$$ \tau_{\text{dyn}} = \frac{1}{\sqrt{2\pi G \rho}} \quad = \quad 1.55 \times 10^5 \left(\frac{n_{\text{H}_2}}{3 \times 10^4 \text{cm}^{-3}}\right)^{-1/2} \text{yr}. \quad (40) $$

Core collapse and formation of a subsequent core takes $\sim 5$ and $\sim 10$ dynamical time scales, respectively. Since the time scale for chemical evolution is $\sim 10^6$ yr, it is comparable to time scales for collapse and propagation of fragmentation only when $n_{\text{H}_2} \gtrsim 3 \times 10^4 \text{cm}^{-3}$. Accordingly we can observe cores of different chemical compositions only in a dense core which can be selected from a C$^{18}$O map.

In fact, such a chemical difference is observed in several clouds in the Taurus region. Good examples are TMC-1C and TMC-1A. These clouds are visible on the C$^{18}$O map (Cernicharo & Guélin 1987). TMC-1C has an elongated structure from SE to NW with
a linear size of $0.3 \times 0.1$ pc (Cernicharo, Guélin & Askne 1984; Yamamoto et al. 1993). The NH$_3$ map reported by Benson & Myers (1989) has a peak at the southeast part of the core, whereas the CCS map has an additional peak at the northwest part (Yamamoto et al. 1993). Thus a significant chemical gradient can be seen along the major axis of the cloud. In this case, the SE core is considered to be older than the NW core, and hence, the cores are being formed successively from SE to NW.

A similar chemical gradient is also seen in the TMC-1A region, as reported by Cernicharo et al. (1984). The distribution of NH$_3$ has a peak at the infrared source position (IRAS 04365+2535). On the other hand, the emission from carbon chain molecules, HC$_3$N and HC$_5$N, tends to be intense in the 5′ north position, although these molecules are not fully mapped in this region. Therefore, the southern part of TMC-1A seems to be in an advanced stage of cloud evolution. It is interesting to note that a high-velocity outflow has recently been detected toward the infrared source (Terebe y, Vogel & Myers 1989; Hirano 1993), indicating that star formation has already taken place in the southern region. Although a few examples of a chemical gradient in the dense cores have been reported, as mentioned above, more extensive observations of NH$_3$ and carbon-chain molecules would be indispensable for observational confirmation of the sequential core (star) formation in filamentary clouds proposed in the present paper.

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\begin{table}
\centering
\begin{tabular}{cccccc}
\hline
$c_s$ & $k_{\text{max}} R$ & $\lambda$ & $i\omega_{\text{max}}$ & $v_{\text{frag}}$ \\
\hline
0.9 & 0.7559 & 8.312 & 0.5142 & 0.756 $c_s$ \\
1.0 & 0.6436 & 9.763 & 0.4142 & 1.231 $c_s$ \\
1.1 & 0.5345 & 11.756 & 0.3142 & 1.512 $c_s$ \\
1.2 & 0.4225 & 14.871 & 0.2142 & 1.711 $c_s$ \\
1.4 & 0.1008 & 62.358 & 0.0142 & 1.985 $c_s$ \\
1.4142 & 0.0 & $+\infty$ & 0.0 & 2.000 $c_s$ \\
\hline
\end{tabular}
\caption{Dispersion Relation for 1D Model Filamentary Cloud}
\end{table}
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Fig. 1.— The time evolution of model 1. The abscissa and ordinate are the $z$-coordinate and time, respectively. The density is denoted by the darkness. The grey scale is shown on the top of the panel. The sound speed is taken to be $c_s = 1.0$.

Fig. 2.— Density and velocity distribution in model 1 at $t = 20$. The upper and lower panels show the density on a logarithmic scale and velocity in a linear scale, respectively. The abscissa is the $z$-coordinate.

Fig. 3.— The same as figure 1 but for model 2 where the sound speed is taken to be $c_s = 1.1$.

Fig. 4.— The same as figure 1 but for model 3 where the sound speed is taken to be $c_s = 1.2$.

Fig. 5.— The same as figure 1 but for model 4 where the initial density density increases from 0.1 to 1.0 in the region $-2.5 \leq z \leq 2.5$. The sound speed is taken to be $c_s = 1.0$.

Fig. 6.— The same as figure 1 but for model 5 where the initial density density increases from 0.1 to 1.0 in the region $-5 \leq z \leq 5$. The sound speed is taken to be $c_s = 1.0$.

Fig. 7.— The same as figure 1 but for model 6 where the initial density density increases from 0.1 to 1.0 in the region $-20 \leq z \leq 20$. The sound speed is taken to be $c_s = 1.0$.

Fig. 8.— The same as figure 1 but for model 4 where the initial density density increases from 0.1 to 1.0 in the region $-50 \leq z \leq 50$. The sound speed is taken to be $c_s = 1.0$.

Fig. 9.— Total integrated intensity maps of CCS (left) and NH$_3$ (right) emission toward TMC-1 (Hirahara et al. 1992). The lowest contour level and the contour interval are 0.4 K km s$^{-1}$. Five cores (A - E) are identified in the filament.