SOME SALIENT FEATURES OF EVOLVING MODELS OF INTERSTELLAR CLOUDS

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ABSTRACT. Difficulties faced by various models of interstellar clouds have been discussed. A new evolutionary model which uses energy equation instead of empirical temperature-density relation used in earlier models has been presented. This calculation shows that for a given initial density, the collapsing cloud has a minimum mass which is significantly smaller than the Jean's mass. The clouds with larger mass than the critical mass continue collapsing and physical and chemical evolution remain similar to earlier evolving models. Clouds with mass smaller than the critical mass initially collapse but ultimately bounce back, producing physically similar clouds in collapsing and expanding phases. The chemical evolution in these two physically similar clouds is different mainly due to differences in their lifetime. The lifetime of this oscillating cloud is also longer than the collapsing cloud.

1. INTRODUCTION

This review paper addresses recent attempts to find a common evolutionary thread through the vast diversity of interstellar clouds. We will see how evolutionary models try to use the observed chemical composition of interstellar clouds for inferring their dynamical destiny. As we go through this review it will become apparent that the the classical constant density-constant temperature models of interstellar cloud chemistry may be inadequate because dynamical motion, both

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quiescent and impulsive, prevent chemistry from attending equilibrium at constant density and temperature.

To put this review in proper perspective, let us start by noting that our understanding of the interstellar medium in general and of interstellar clouds in particular has taken a big step forward in the last two decades because of observations from space platforms like COPERNICUS and IUE in ultraviolet and discoveries of a large number of molecules from millimetre wave observations from the ground. The observations of molecules containing as much as 13 atoms in a low density ($<10^7$ cm^{-3}) and low temperature (~10°K) interstellar clouds have thrown a challenge to astrochemists to provide an adequate theory of formation of these molecules. Astrochemists met this challenge by inventing an ion-molecular reaction scheme which is fast enough even at low densities to provide a workable scenario of formation of molecules in interstellar clouds. To determine the molecular abundances for comparison with observation it is necessary to know physical parameters like density and temperature for the cloud. To start with it was simply assumed to be of constant density and constant temperature (homogeneous and isothermal). The cloud was also assumed to be in steady state which was relaxed later to allow time dependence. Since these early models, models with varying complexity have been built to represent an interstellar cloud as realistically as possible. Most of the models now present can broadly be classified into four categories:

(A) constant density temperature (i.e. homogeneous isothermal) steady state models.
(B) constant density constant temperature (homogeneous isothermal pseudo-time dependent models
(C) hydrostatic (turbulence supported) models
(D) evolutionary models.

Details of models (A)-(C) can be found in recent papers by van Dishoeck and Black (1986), Viala (1986), Viala, Roueff and Abgrall (1987) for diffuse clouds, and in papers by Prasad and Huntress (1980), de Jong, Dalgarno and Boland (1980), Boland and de Jong (1982), Millar and Freeman (1984), Millar and Nejud (1985), Herbst and Leung (1986a,b), Graedel, Langer and Frerking (1982), Watt (1983), Suzuki (1983) for dense clouds. Model (D) can be found in Gerola and Glasgold (1978), and Tarafdar et al. (1985). Different models have been reviewed recently by Langer and Graedel (1987), Black (1987), Hartquist (1987), Wootten (1987), Dalgarno (1987a,b), Herbst (1987), Winnewisser and Herbst (1987), Prasad (1987), Prasad et al (1987) and van Dishoeck (1988a). Further progress in models (A)-(C) and the need of atomic and molecular data in these models will be presented elsewhere in this volume by van Dishoeck (1988b), Black (1988) and Millar (1988). Our aim is to present a few salient features including advantages and difficulties of model (D). But before doing this, let us present some difficulties faced by models (A)-(C), as some of these will be present in model (D) also, and subsequently we shall point out how these difficulties are either removed or alleviated and some others turn out to be advantages in model (D).

2. SOME DIFFICULTIES OF MODELS (A) TO (C).

A common difficulty in models (A) and (C) is the problem of depletion of gas phase molecules onto grains. The time scale of this depletion can be written as $t_d=(s\sigma_g n_g v)^{-1}$, where s is the sticking coefficient, σ_g and n_g are respectively grain cross section and density and v is the thermal velocity of molecules. With $\sigma_g n_g=10^{-21} n_H$ where n_H is the density of hydrogen nuclei and $v=10^4$ cm^2 for interstellar molecules heavier than H_2, $t_d = 3x10^9/(sn_H)$ yrs. As s≈1 for molecules heavier than H_2 (Hollenbach and Salpeter 1970), $t_d \leq 10^7$ yrs for n_H 300cm^{-3}. The lifetime of clouds is 10^7-10^8 yrs. Thus clouds with $n_H>300$cm^{-3} will be devoid any gas phase molecule unless some efficient desorption mechanism is found to bring back molecules from grain surfaces. Several desorption mechanisms (cf. Boland and de Jong 1982, d'Hendecourt et al. 1982, Williams and Hartquist 1984, Leger, Jura and Omont 1985) have been proposed, but it is not yet clear whether any one of these or together can work in real clouds to avoid the depletion problem in models (A)-(C). We shall see later how the depletion problem is alleviated in evolving models (D).

A common problem present in constant density constant temperature models (A) and (B) is the energy balance in the cloud. In the absence of any internal stellar source in an interstellar cloud (i.e. when the cloud is not circumstellar) the source of energy of the cloud is from outside as cosmic rays and average ultraviolet radiations from O- and B-stars. The ultraviolet radiation intensity decreases from the cloud surface inward due to grain attenuation. Thus the heating rate (Γ) at an optical depth point Av can be written as

$$\Gamma=[\Gamma_c + \Gamma_{uv} \exp(-\alpha A_V)] n_H \text{ ergs cm}^{-3} \text{ s}^{-1} \tag{1}$$

where α is a constant, n_H is the density of hydrogen nuclei and Γ_e and Γ_{uv} are respectively the heating rates due to cosmic rays and ultraviolet radiation at the cloud surface. The cooling of the interstellar cloud is by line emission as a result of spontaneous decay of an upper level excited collisionally. Hence the cooling rate (Λ) can be represented approximately as

$$\Lambda=\Lambda_o n_H n \exp(-E/kT) \text{ ergs cm}^{-3} \text{ s}^{-1} \quad , \tag{2}$$

where k is the Boltzman constant, T is the temperature, E is the excitation energy, n is the density of the coolant and Λ_o is a constant of dimension ergs cm^3 s^{-1}. Equating the heating rate to the cooling rate and putting $\Gamma_c=0$ for simplicity, the temperature T at optical depth A_V can be expressed as

$$T = \frac{E/R}{\alpha A_V + \ln \frac{\Lambda n}{\Gamma_u}} \tag{3}$$

Eq. (3) shows that T decreases as A_V increases. Thus for a homogeneous cloud (i.e., n=constant), the temperature should decrease inward for a realistic interstellar cloud. Therefore, isothermal assumption of models (A) and (B) cannot be right for an interstellar cloud.

The difficulty of maintaining constant temperature in homogeneous clouds becomes an advantage for evolving clouds, because for a homogeneous cloud the inward decrease of temperature gives an inward force which helps the gravity to collapse the cloud to a higher density. As density increases the inside temperature drops further (eq. 3) adding the gravity to collapse the cloud further. Thus the inward decrease of temperature in interstellar clouds is the key point of evolutionary models and helps in collapsing a cloud with much lower mass for given density or with much lower density for a given mass than that which is possible under Jean's criteria.

3. AIMS OF EVOLVING MODEL

The basic aims of evolving model is to seek answers to questions like how different variety of interstellar clouds came to the state where they are, do they change with time and if so in what way this change takes place, how does the cloud evolution fit with the evolutionary sequence of other set of objects like stars. For example we would like to find out whether a link exists between interstellar clouds from diffuse to dense phase. A link in the sense that one type of clouds evolves to another in time will be very satisfying as it will establish an order among variety of clouds from diffuse to dense and avoid arbitrary nature of their presence.

4. EVOLVING MODELS

The basic equations of evolving models are:

conservation of mass, $$\frac{\partial m(r)}{\partial r} = 4\Pi r^2 \rho(r) \quad (4)$$

conservation of momentum, $$\frac{\partial^2 r}{\partial t^2} + \frac{1}{\rho}\frac{\partial P}{\partial r} + \frac{Gm(r)}{r^2} = 0 \quad (5)$$

conservation of energy, $$\frac{\rho}{\mu}\frac{d}{dt}\left(\frac{3}{2}kT\right) - \frac{kT}{\mu}\frac{d\rho}{dt} = \Gamma - \Lambda \quad (6)$$

radiative transfer equation, $$\frac{dI_\nu}{d\tau_\nu} = - I_\nu + S \quad (7)$$

and

rate equations (i-1,..n) $$\frac{dn_i}{dt} = \text{formation-destruction rates.} \quad (8)$$

These equations are supplemented by

equation of state, $$P = R\rho T/\mu \quad (9)$$

heating rate, $$\Gamma = \Gamma(n_H, T) \quad (10)$$

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and

$$\textit{Cooling rate, } \Lambda = \Lambda(n_H, n_i, T) \quad . \tag{11}$$

Ideally, equations (4)-(11) need to be solved simultaneously to obtain physical variables like density ρ, temperature, T, pressure, P, radiation intensity I_V and chemical composition $n_i(i=1...n)$ as a function of space variable r and time t. However, such a solution of equations (4)-(11) will be very time-consuming, as chemical reate equation (8) has to be for a large number of species, even if we want to cover a limited number of observed molecules. Therefore, we need to make some drastic simplification. In order to do this without loosing the basic physics of interstellar clouds, in Tarafdar et al. (1985) the energy equation which connects the dynamical equations with chemical equations through the cooling rate has been replaced by an empirical relation between temperature, density and optical depth of the form:

$$T = 163/[2.5+\ln n_H - \ln\{+1+500 \exp(-1.8A_V)\}] \quad . \tag{12}$$

The different constants are so chosen to fit the dependence of T on A_V and n_H given by de Jong et al.(1980). Note that relation (12) maintains the physical behavior of T in interstellar clouds pointed out earlier that T decreases as A_V increases. Further, the radiative transfer equation was replaced by a simple solution of the form $I_V=I_V^\circ \exp(-\alpha_V A_V)$, where α_V was determined from interstellar extinction laws, I_V° being the unattenuated interstellar background field. The details of this calculation and result have been presented in Tarafdar et al. (1985).

Three conservation equations (4)-(6) have now been solved simultaneously instead of the assumption of empirical temperature relation (12), but assuming as before that $I_V = I_V^\circ (\exp(-\alpha_V A_V)$ and cooling is only by CII and CO. Further individual cooling rates of CII and CO have been replaced by a common cooling which is the same as CII cooling, assuming $n(CII)/n_H = 7.5\times10^{-5}$ throughout the cloud. The solution of equations (4)-(6) then gives $\rho(r,t)$ and $T(r,t)$ which have been used to solve rate equations(9) including a large number of species involving about 2000 reactions starting with the initial condition that all hydrogen are in the form of HI, all carbon in the form of C^+, oxygen in the form of OI, and all nitrogen are in the form of NI. Note that the subsequent chemical results do not depend on these initial values which are appropriate for diffuse interstellar clouds, as chemical equilibrium sets in soon because of longer dynamical time scale of the diffuse phase.

5. SOME RESULTS OF EVOLVING MODELS

5.1 Lowering of Jean's Mass

Now we present a couple of significant results. The first task confronting evolutionary models is the determination of the range of their applicability. For this purpose we must examine whether lower limit of

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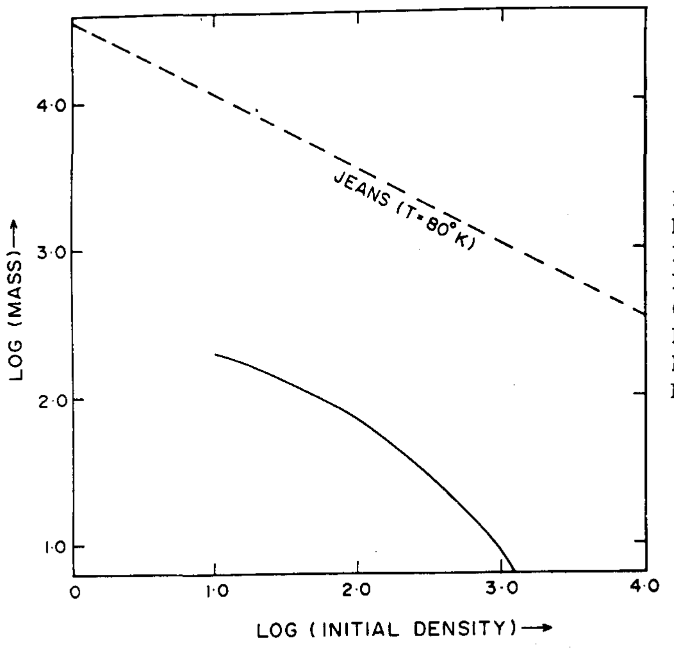

FIG. 1: VARIATION OF MIMIMUM MASS OF COLLAPSING CLOUD AS A FUNCTION OF DENSITY: CONTINUOUS LINE-PRESENT CALCULATION AND DASHED CURVE-JEANS MASS AT 80°K.

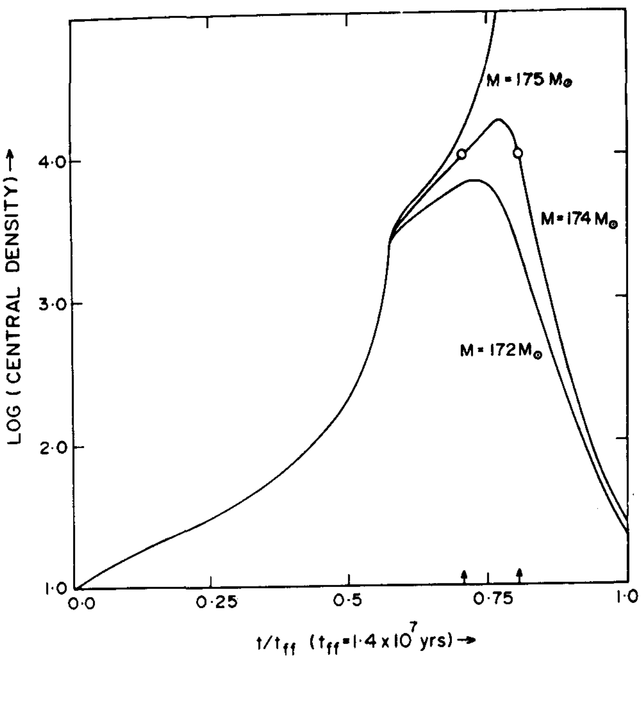

FIG. 2: VARIATION OF CENTRAL DENSITIES OF EVOLVING CLOUDS OF MASSES $175M_\odot$, $174M_\odot$, $172\ M_\odot$ WITH TIME. CENTRAL DENSITY INCREASES WITH TIME FOR $175M_\odot$ CLOUD BUT PASSES THROUGH A MAXIMUM FOR CLOUD OF MASS $174M_\odot$ PRODUCING TWO PHYSICALLY SIMILAR CLOUDS AT DIFFERENT PHASES (MARKED WITH DOTS) OF ITS EVOLUTION.

mass or density of a cloud, for collapse, can be lowered from those given by Jean's criteria. Starting the collapse at density as low as $10 cm^{-3}$ has the advantage of having a long-lived collapsing cloud for observation bringing the star formation under the realm of direct observation.

Fig. 1 shows the variation of minimum mass of a cloud which can collapse as a function of initial density. For comparison the variation of minimum mass from Jean's criteria with T=80°K has also been shown (dashed line). The figure shows that the minimum mass for a given density is significantly lower than the corresponding Jean's mass. Thus for an initial density of 10^3 cm^{-3}, a cloud with as low a mass as 10 $M_\odot$ can now be collapsed, whereas according to Jean's criteria, the necessary cloud mass is over 10^3 $M_\odot$. The figure also shows that for a given mass the density necessary for the cloud to collapse has also been lowered significantly. As for example, for a cloud of 200 $M_\odot$ mass to collapse, the necessary density is now of the order of 10 cm^{-3}, but according to Jean's criteria a density over 10^4 cm^{-3} is required. The lowering of mass and density for a cloud to collapse is the direct consequence of the proper treatment of the energy equation which gives an inward force due to inward temperature decrease in an interstellar cloud. Note that an isolated mass of stellar size can now collapse starting from realistic interstellar density and all stars need not form in clusters due to fragmentation of a large cloud. Moreover, as the collapse can start at a density of 10 cm^{-3}, the cloud lifetime is about 10^7 years, which is long enough for observation.

5.2 A Common Link between Diffuse and Dense Clouds

The variation of density and temperature with radius and time for a cloud of given mass larger than the minimum mass remains similar to those obtained earlier with empirical temperature-optical depth relation (Tarafdar et al. 1985). Therefore, the variation of column densities of various molecules with A_V remains the same as in previous models (Tarafdar et al. 1985), as long as the involved reaction rates are kept the same. Thus the agreement noted between the theoretical and the observed variation of column densities of CI and CO with A_v holds. The agreement suggests that the interstellar clouds from diffuse to dense are linked by evolution in the sense that a diffuse cloud evolves to a dense cloud after sufficient time has elapsed. This brings our aim into successful completion.

5.3 Oscillating Clouds and Their Properties

In order to examine the dynamical and chemical evolution of a cloud with mass smaller than the critical mass given in Fig. 1, we have evolved clouds with three masses of 175 $M_\odot$, 174 $M_\odot$ and 173 $M_\odot$. The initial homogeneous density for all clouds has been assumed to be 10 cm^{-3}. Fig. 2 shows the variation of central density with evolution time for these models. The figure shows that the central density of 175 $M_\odot$ cloud increases indefinitely, whereas it reaches a maximum for 174 $M_\odot$ and 173 $M_\odot$ at around t=0.75 t_{ff} and decreases thereafter. This rebounce back is due to competing effects of temperature and density gradient forces

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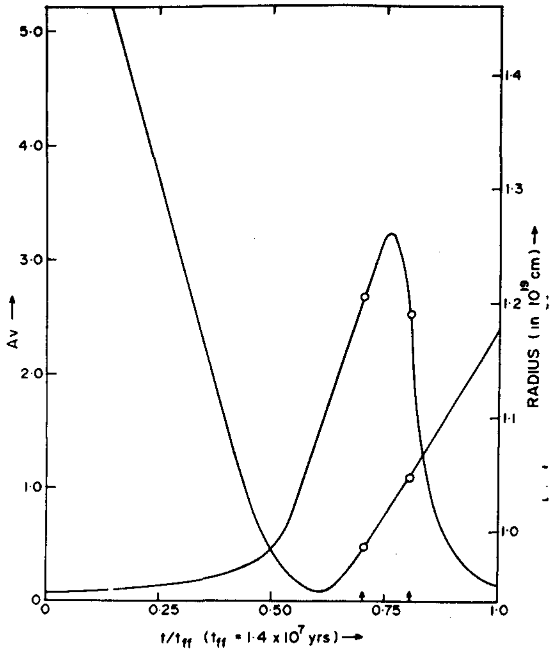

FIG. 3: VARIATION OF CENTRAL A_V AND RADIUS OF THE CLOUD OF $174M_{\odot}$ AS A FUNCTION OF TIME. DOTS SHOW THE TWO PHASES WHERE CENTRAL DENSITIES ARE SAME. FIGURE SHOWS THAT A_V AND RADIUS AT THESE TWO PHASES OF EVOLUTION ARE ALSO SAME IMPLYING PHYSICAL SIMILARITY BETWEEN CLOUDS AT THESE TWO PHASES.

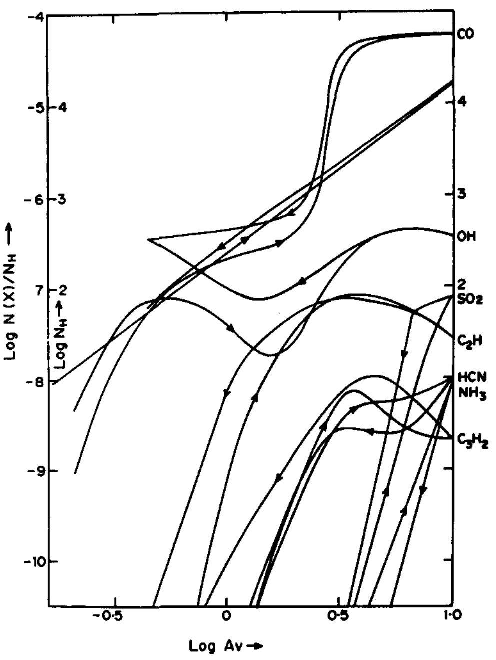

FIG. 4: VARIATION OF FRACTIONAL ABUNDANCES OF VARIOUS MOLECULES WITH A_V IN COLLAPSING (MARKED WITH ARROW TOWARDS INCREASING A_V) AND EXPANDING (MARKED WITH REVERSE ARROW) PHASES. NOTE THE ABUNDANCE DIFFERENCE IN TWO PHASES WITH SAME A_V.

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which act in opposite sense. Thus the clouds, with mass smaller than the critical mass for collapse, initially contract and expand after attaining a maximum central density. This oscillation has significant physical and chemical consequences. Note that the central density has same value (marked by dots in 174 $M_{\odot}$ curve) of 10^4 cm^{-3} at two different times.

Fig. 3 shows the variation A_V and cloud radius R of 174 $M_{\odot}$ cloud as a function of evolving times. The dots in A_V and R curves correspond to the phases where the central density was the same as marked in Fig. 2. Note that the values of A_V and R are observationally indistinguishable in two phases of contraction and expansion of the cloud. Thus evolution of clouds with mass smaller than the critical mass will produce two physically similar clouds at two different times of its evolution. As chemical evolution is time dependent, the contracting and expanding clouds will have different chemical compositions. This is clear from Fig. 4 which shows the variation of abundances of a few molecules relative to that of hydrogen nuclei (i.e. $N(x)/(N_{HI} + 2N_{H_2})$) as a function of A_V. Note that A_V increases in the contracting phase and decreases in expanding phase with time. The curves giving molecular abundances in the contracting phase have been marked with arrows pointing toward large A_V. An arrow in the reverse direction indicates the abundances in the expanding phase. The figure shows that as expected, the molecular abundances may be different depending on whether the cloud is in contracting or expanding phase. The figure also shows that abundances of some molecules may be the same but others could be different in two phases. Whether an abundance of a particular species will be different or the same depends on A_V (i.e. on the phase of evolution). The possibility of having two physically similar but chemically different clouds has observational counterpart in TMC-1 and L134N which are physically similar but chemically different (Irvine, Goldsmith and Hjalmarson 1987).

6. DIFFICULTIES OF EVOLVING MODELS AND THEIR POSSIBLE REMEDIES

One of the difficulties of evolving models is its short lifetime compared to the generally accepted interstellar cloud lifetime of 10^7–10^8 yrs. The model reported by Tarafdar et al. (1985) has a lifetime of about 4×10^6 yrs which is a factor 2.5 smaller than the accepted cloud lifetime. The short lifetime of evolving models resulted as they started with an initial density of about $150 cm^{-3}$. The present model starts with initial density of $10 cm^{-3}$ and hence increases the lifetime to 10^7 yrs. (Fig. 2) The lifetime of the cloud will further increase, if the effect of turbulence which has been ignored in these models, is included in the models. Moreover, if some of the interstellar clouds are oscillating, as shown above is possible, if their mass is appropriate, the problem of short lifetime of evolving clouds is further alleviated.

Lastly the depletion of gas phase molecules is also a problem in evolving clouds, though it is not as severe as it is in steady state models. This is because an evolving cloud spends most of its lifetime in the diffuse phase and a time $t_e = 4.1\times10^7/n_H^{1/2}$ yrs in the phase having density of n_H. Thus depletion becomes important in evolving models only at density higher than 5.0×10^3 cm^{-3}. This density can further be increased by proper treatment of cooling agents in the dense phase of its evolution. However, it is highly unlikely that depletion will be non-existent in these models at densities of 10^5-$10^6 cm^{-3}$ unless some desorption mechanisms operate at that stage of evolution.

7. CONCLUSION

As can be seen from the above presentation and from Tarafdar et al. (1985), the evolving models even in their approximate form have been able to satisfy the goal of unifying the variety of interstellar clouds into an evolutionary sequence in the sense that a diffuse cloud evolves to a dense cloud. The apparent difficulties like short lifetime of the cloud and large star formation rates due to cloud evolution can be overcome by improved treatment of physical processes or by realizing that only the core of the cloud is to evolve into a star. The real test of evolving models and their usefulness in explaining and using observed molecular abundances to infer about the physical state of the cloud will come when better models and better determination of molecular abundances are available.

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