EVOLUTIONARY MODELS OF INTERSTELLAR CHEMISTRY

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ABSTRACT. Evolutionary chemical models are ultimately unavoidable for a full understanding of interstellar clouds. They include not only the chemical processes but also the dynamical processes by which the modeled object came to be the way it is. From an evolutionary perspective, dark cores may be ephemeral objects and dynamical equilibrium an exception rather than norm. Evolutionary models have numerous advantages over "classical" fixed condition equilibrium models. They have the potential to provide more elegant explanations for the observed inter-cloud and intra-cloud chemical differences. The problem of the depletion of gas phase molecules by condensation onto the grain may also be less serious in evolutionary models. Hence, these models should be actively developed.

1. EVOLUTIONARY MODELS ARE ESSENTIAL:

Impressive strides are being made in the observations of molecular clouds. *Do we have matching quality theoretical tools for data interpretation? Unfortunately not.* Currently fixed condition equilibrium models are the most widely used tool for elucidating observed molecular abundances. In these models the physical conditions of density, temperature and visual extinction are kept fixed. Table 1 compares these models with evolutionary models which consider, not only the chemistry, but also the mediating dynamical processes by which the objects came to be the way they are. In evolutionary models, therefore, the physical conditions are allowed to change with time in response to known quantifiable dynamical processes and/or external environmental conditions. Due to lack of space, consider just the non-equilibrium nature of the chemistry in even dark clouds away from active star forming region (Herbst and Leung 1986, 1989) and/or the survival of the molecules in the gas phase in those clouds despite their efficient absorption onto the cold grains from which efficient desorption is still uncertain. Their explanations in fixed condition "classical" models involves mixing currents (Chièze and Pineau des Forêts 1987, Chièze et al 1991). But this has not worked well. The latest mixing model finds it necessary to introduce elements of evolutionary modeling. This need was fulfilled in an improvised manner, *e.g.*, exponential evolution of density and power law growth of visual extinction with time (Chièze et al 1991). Given this experience with fixed-condition models, realistic evolutionary models are ultimately unavoidable. Fixed condition "classical" equilibrium models do not mean much, especially when arbitrary elements are introduced to generate agreement with observations.

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Table 1. Comparison of the "classical" and evolutionary models

Model Type	Merits	Demerits
"Classical" or Fixed-Condition equilibrium models [Density, temperature & visual extinctions, and their spatial variations in the cloud are held fixed]	● Simplicity ● Chemical production & loss processes easily understood ● First order feel for which molecule trace what regions of the clouds	● Non-equilibrium chemistry, inter-cloud & intra-cloud chemical variations, and depletion of molecules by the grains have *ad hoc*, rather artificial solution ● Cloud structure taken for granted. Lots of interesting (intermediate) phenomenon lost ● Diffuse, translucent and dark objects unrelated
Evolutionary Models [Cloud Structure changes with time in response to known quantifiable dynamical processes]	● All of the above minus simplicity ● Includes equilibrium models as a subset ● (i) Better understanding of the non-equilibrium chemistry and of the inter-cloud & intra-cloud variations, and (ii) the grain absorption problem less serious ● Diffuse, translucent & dense clouds need not be unrelated	● <u>None</u> of the above but ● Computationally demanding ● Analysis of results more laborious (although rewarding)

2. TYPES OF EVOLUTIONARY MODELS:

Evolutionary models can be driven in a number of ways, all depending upon the objects and their environment. Following two classes of evolutionary models are relatively more developed:

(i) In the region of active star formation (*e.g.*, M17 SW, Bernard 5) evolution of interstellar gas between dense and diffuse phases and the non-equilibrium nature of the chemistry can be sustained by the stellar winds. Williams and his collaborators (*e.g.*, Williams and Hartquist 1984, Charnley et al 1988a,b) have made evolutionary models of interstellar chemistry driven by stellar winds. Their models have four evolutionary phases: (1) collapse of dense cores and the freeze-

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out of molecules onto the grains, (2) ablation of cores by stellar winds, (3) arrest of wind flow by weak reverse shock, and (4) accumulation of dense post shock gas into the core. These have been reviewed by Charnley (1992).

(ii) The other class of evolutionary models, on which we have focussed, are for quiescent dark cloud cores mostly isolated from energetic processes associated with nascent stars. These objects are either far away from concentrations of young stars, or the concentration of stars near them is too small to be important. L134N is currently thought to be an example of such an quiescent object, as evidenced by its narrow line widths indicating the absence of shocks or supersonic velocities. High latitude clouds (or, the cirrus) are additional examples. Our aim has been to understand inter-cloud and intra-cloud variations of molecular compositions in this class of objects. We were also motivated to provide a frame work for a more refined understanding of the epochs (i) and (iv) of the evolutionary models dominated by stellar winds.

In addition to the above two categories, evolutionary models may also be based on the formation of denser clouds by cloud-cloud collisions (Henriksen and Turner 1984, Elmegreen 1987), or on the formation and decay of clumps of moderate densities by fluctuations in the uv radiation field (Chièze and Boisanger 1991).

3. MILESTONES IN SIMPLIFIED EVOLUTIONARY MODELS OF DARK CLOUD CORES:

This class of models have come a long way. In 70s, free fall or arbitrarily retarded free fall of isothermal interstellar gas was used to model the molecule rich dense cloud cores (Kiguchi et al 1974, Suzuki et al 1976). Gerola and Glassgold (1978) model was an exception to these rather crude modeling, because it involved both gravity and pressure gradient forces in the equation of motion which was solved simultaneously with the continuity and heat budget equations. Unfortunately, this model was never implemented beyond the single case of a quite massive (1000 solar mass) cloud which was further restricted to being already dense to start with (initial density = 10^3 cm^{-3}). These restrictions may have been the consequence of the then prevailing notion that low mass diffuse clouds generally do not collapse gravitationally.

By mid-80s, a major advance occurred when we showed that even low mass warm diffuse clouds could easily contract to form dense cores (Tarafdar et al 1985). Due to the extinction of the background interstellar uv radiation with depth, the model clouds were always warmer at the outer edges compared to the inner regions. There was, therefore, a pressure gradient force that assisted gravity in initiating the contraction of even low mass warm diffuse clouds. These models, however, generated one serious concern. Formation of dense cores in this way, it was argued by the critics, would lead to star formation rate in excess of the observed. We responded to this concern by including forces that may oppose gravity, and by including lower initial densities.

The forces that may oppose gravity and increase in strength with the density were mimicked by tangled frozen-in magnetic fields. They lead to outward directed magnetic pressure gradient force whose magnitude increases as the core density increases. The gravitational contraction is now no longer always monotonic. Depending on the initial magnetic field strength, gravitationally contracting clouds may follow a star forming track (monotonic contraction to a protostellar stage)or a non-star forming track along which they would revert back to the diffuse state after reaching high core densities. Frozen-in magnetic field is not the only mechanism to reverse a gravitational collapse. Lower initial densities can produce similar effects in non-magnetic clouds (Tarafdar et al 1989). Thus, the key points are: (i) contraction is reversible under a variety of conditions, and (ii) this reversal eliminates conflict with the observed star formation rate.

4. EVOLUTION MAY BE THE NORM:

It now appears that dark cloud cores may be transient, not long-lived, objects even in the absence of harsh stellar influences. They may be just one epoch in the incessant dynamical evolution. Contrary to the common belief, dynamical equilibrium may be exception rather than the norm. Indeed, the notion of all pervading dynamical equilibrium has serious problems. Cox (1990) and Turner et al (1991) have pointed out one difficulty with respect to diffuse clouds, *viz.*, "How the heating mechanism manages to provide just the right amount of energy so that diffuse clouds have thermal pressures that can be easily confined"? Dark cores present similar problems. "While it is easy to determine a set of conditions that will hold a dark core in equilibrium, it is much more difficult to ensure that exactly those conditions will be seen by the core in the course of its formation" (Prasad et al 1991). Evolutionary models do not have these difficulties. In addition, they have the potential to provide a more natural explanation of the observed inter-cloud and intra-cloud chemical differences. Prasad et al (1991) give an example of this potential in the context of the cloud-to-cloud variation of the HC_3N abundance (see their Figure 17)

5. RESPONSE TO THE COMMON OBJECTIONS TO EVOLUTIONARY MODELS OF DARK CORES:

As with any new idea, objections may continue, for sometime, to be raised against evolutionary models of dark clouds. One objection is that the dark cores obey the virial equations. This objection is not serious, because the dark cores obey the equations only crudely. The second objection argues that no one has ever observed a contracting/expanding dark core. This may, however, be a detectibility issue (A. Dalgarno, private communication). No one can deny that stars are forming, and therefore at least some clouds are gravitationally contracting. Why, then, even those are not detected? The answer is that realistic dynamically evolving dark cores have very small systematic velocity in the region where the molecular tracers of high density reside. This is easily verified for NH_3 by inspecting figures 4 and 13 of Prasad et al (1991). Non-detection of contracting/expanding cores, therefore, can not stand as an argument against evolutionary models.

6. LIMITATIONS OF THE PRESENT EVOLUTIONARY MODELS OF DARK CORES:

The present evolutionary models have limitations, because we considered the cloud to be homogeneous and ignored the observed clumpiness. Even so, the models are applicable to select high latitude dense clouds, some dark clouds (*e.g.*, L134N) which are not excessively clumpy, and possibly to individual clumps of a clumpy cloud depending on the clumps' mass, environment and origin.

7. SUMMARY:

Evolutionary models are essential for a proper understanding of interstellar clouds. In contrast to the more common fixed condition equilibrium models, the evolutionary models allow the conditions in the modeled objects to change with time in response the mechanisms by which the objects came to be way they are. These models imply that dark cloud cores may be dynamically evolving short-lived objects, even in the absence of stellar influences. There are probably no very solid reasons to doubt the that dynamically evolving objects may the norm and dynamical equilibrium the exception. Furthermore, the concept of ubiquitous equilibrium has some problems both in the dense and diffuse regions. Dynamically evolving models have the potential to provide a more natural explanation of the observed inter-cloud and intra-cloud chemical variations. These models should, therefore, be vigorously developed so as to reduce their limitations and increase their applicability.

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QUESTION AND ANSWER

B.E.Turner: While polytropic hydrostatic equilbrium models of index N=-3 can explain $C^{18}O$ observations (J=2-1,1-0) in many cirrus cloud cores (Turner et al.1991), they cannot explain $C^{18}O$ observations in cold dark clouds of higher density. These latter have non-equilbrium chemistry, as distinct from the equilbrium chemistry that describes cirrus cloud cores, hence require a mixing within the cloud material. The idea of Prasad et al. that magnetic fields can produce such "turning" made out of the core region, thus renewing the chemistry, also produces a flatter density distribution with radius than can hydrostatic equilbrium or most dynamical collapse models. Such a flatter distribution is precisely what is needed to explain the $C^{18}O$ observations of these cold dense clouds.

S.S.Prasad: Thank you, Barry, for your constructive comment. The possibility that your observational data can differentiate between hydrostatic model, on the one hand, and various dynamical models, on the other hand, is quite significant. This should provide the much needed stimulus to build better models with useful physics content.