DYNAMICAL CONDITIONS OF DENSE CLUMPS IN DARK CLOUDS : A STRATEGY FOR ELUCIDATION

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Abstract. Chemical considerations and simplified dynamical modeling suggest that dark cloud cores may be incessantly evolving such that the time spent at high core densities decreases as the density increases. After reaching a high density, gravitationally contracting dark cloud cores may either form stars or expand to states of lower densities. Cloud mass and initial density are amongst the factors that may control the evolutionary fate of the core. This view is diametrically opposite of the common belief that dense cores may be in near mechanical equilibrium. Mutually consistent end-to-end modeling of the spectral line profiles and intensities is needed to discern the reality.

1. Introduction

The dynamical conditions of the dense clumps or cores in molecular clouds are discussed from the perspective of chemistry. This discussion suggests the possibility that dynamical evolution, rather than dynamical equilibrium, may be the norm for these clumps at least for dark clouds.

Reviews presented in this IAU Symposium leave little doubt that molecular clouds are very clumpy (e. g., Thaddeus 1990, Solomon 1990). This conclusion has been reached by panoramic surveys in CO lines (Thaddeus 1990, Solomon 1990), and has been substantiated by cloud specific surveys in the lines of other molecules (e. g., CS, NH_3) capable of acting as high density tracers (e. g., Swade 1990). A precise definition of clumps is, however, not available at the present time (Myers 1990). Indeed, the words clumps and cores have been used interchangeably. Nevertheless, in general terms, clumps or core are regions of enhanced density surrounded by regions where the density drops significantly by two to three orders of magnitudes. The number and sizes of the clumps in a given cloud may vary significantly from cloud-to-cloud. According to a model by Tauber and Goldsmith (1990), the OMC may contain thousands of small clumps of at best a few solar mass. In contrast, L134N in the Taurus region may have only a few massive clumps of about 25 solar mass. The cause of this vast diversity is not known. However, it is noteworthy that clouds modeled by Tauber and Goldsmith (1990) are associated

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with active star formation while L134N appears to be quiescent and perhaps only on the threshold of star formation.

While panoramic surveys indicate the presence of clumps, these maps of line intensities provide no information about the dynamical conditions in the clumps or cores. The dynamical conditions have, therefore, been inferred from the width and shapes of the spectral lines. This is possible because $\Delta\nu$, the line width in the frequency domain, is directly related to σ, the velocity dispersion. Indeed, the line widths are usually expressed as Δv where v is the velocity.

Molecules can also be used to infer the dynamical conditions in the dense clumps or cores because the abundances and the line intensities of at least some of them are sensitive to the dynamical states. For example, the abundances of "complex molecules" (e. g., C_2H, C_3H, C_3H_2) are much smaller in the equilibrium models, compared to the models in which the chemistry is prevented from equilibrating by the dynamics. By comparing the observed abundances (preferably line intensities) of the sensitive molecules with the theoretical predictions for the equilibrium and evolutionary models, it should be possible to form a consensus about the dynamical states of the targeted cloud cores.

2. Contrasting Views About the Dynamical States of the Clumps :

According to one school, the dense clumps or cores are thought to be in near mechanical equilibrium and probably magnetically supported (Myers 1983), because they approximately obey the relations of virial balance ($\sigma^2 \simeq GM/R$), and (Larson's) power law relation ($\sigma \simeq R^{0.5}$) and ($n \simeq R^{-1}$). In these relations, n, M and R are the cloud density, mass and size, and σ is the velocity dispersion which is related to the spectral line widths. If these objects were collapsing on a free fall time scale, it is argued, then the star formation rate in the galaxy would be too high (Zuckerman and Palmer 1974).

A diametrically opposite state of dark cloud cores is, however, suggested by their observed molecular abundances.

If these cores are in near equilibrium, then their molecular abundances should reflect chemical equilibrium at fixed conditions of density, temperature and visual extinction. The observed abundances show serious disagreement with equilibrium chemistry abundances (Herbst and Leung 1986a,b, 1989). The equilibrium chemistry tends to under-estimate the abundances of long carbon chain molecules (complex molecules) and over-estimates the abundances of H_2O and O_2 (Chièze and Pineau des Forêts 1989).

One possible solution of this chemical dilemma is to assume the existence of mixing currents which bring core material to the envelop at short time intervals and limit the time available to chemistry to equilibrate at any fixed conditions of density, temperature and visual extinction (Boland and de Jong 1984, Chièze and Pineau des Forêts 1989). Williams and Hartquist (1984) have, however, pointed out significant difficulties with this solution. These difficulties are all the more accentuated in dark cloud cores, where turbulent line widths are quite small (Swade 1990). Penetration of *uv* due to extreme clumping (Boissé 1990) may work only for cores near star formation in giant molecular clouds. The other possible solution is that dark clouds may be gravitationally evolving, so that the cloud cores spend only a limited time at any given core density, and this time decreases as the core density increases (Tarafdar et al 1985, Prasad 1987, Prasad et al 1987). In these models the time available for dark cloud core chemistry to equilibrate is severely restricted, and the modeled chemical composition of these cores are in better agreement with observations (Tarafdar et al 1985). These early evolutionary models were, however, susceptible to criticism that they imply excessive star formation rate.

3. Improved Evolutionary Models

Recent improved evolutionary models have the potential to avoid the above-mentioned conflicts with the observed star formation rates. This follows from the theoretical result that all gravitationally contracting clouds may not form star; some may expand after attaining high core densities and revert to a diffuse state.

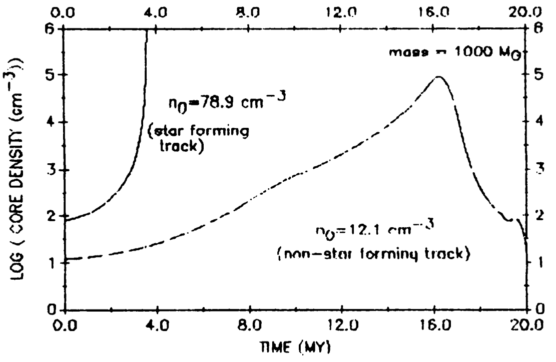

Fig. 1. Time evolution of the core density in a gravitationally contracting cloud of $1000M_\odot$.

Improved evolutionary models span lower initial densities and also include non-gravitational forces that may oppose gravity. Modeling details have been presented by Prasad et al (1990). Here we discuss the results only. Figure 1 shows the time evolution of the core density in a model cloud of $1000M_\odot$ gravitationally contracting from initial densities of 12 and 79 atoms cm^{-3}. When the initial density was high (e. g., $n_0 \geq 78$ cm^{-3}) the cloud collapsed monotonically on a star-forming track. It attained a core density of 10^3cm^{-3} in about 3 MY. After that the core density increased rather rapidly and very soon the cloud was on the threshold of star formation. In sharp contrast, the cloud evolved on a non-star-forming track when the initial density was low, say, only 12 cm^{-3}. In this case, the initial evolution towards the higher core densities was very slow. It took 12 MY to reach the core density of $10^3 cm^{-3}$. Thereafter the core density increased relatively more rapidly, so that a 100 fold increase in the core density took place in only 4 MY. At this stage, however, an interesting phenomenon occurred. The cloud began to expand and its core density started to decrease. In the course of the initial contraction, the pressure gradient forces increased more rapidly than the gravity. This should explain the subsequent expansion by which the cloud reverts to its initial diffuse state.

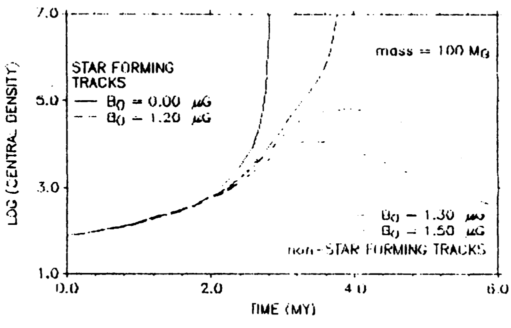

Fig. 2. Time evolution of the core density in model clouds of $100M_\odot$. The clouds differed in the values of the initial strength of the tangled frozen-in magnetic field.

Similar behaviors were exhibited by model clouds with non-gravitational forces capable of opposing gravity. In the present study, those forces were mimicked by randomly oriented frozen-in magnetic fields which increased with density according to a power law $B = B_0(\rho/\rho_0)^k$ where $k = 2/3$ was assumed. It is recognized that the existence of tangled frozen-in magnetic field is by no means certain. Even so, it has been used here as a simplified surrogate for a number of physical processes that may oppose gravitational contraction in such a manner that the opposition increases as the core density increases. One example is the progressive removal of coolants (e. g., CO) from the gas phase by condensation onto the grains which might produce a warmer core and thereby a stronger thermal pressure gradient force opposed to gravity. Figure 2 shows the results for a cloud of $100M_\odot$ with an uniform initial density of $79 cm^{-3}$. The higher initial density was chosen because, with reference to the data presented in Fig. 1, clouds with this high initial density have a greater tendency to follow star-forming evolutionary track. Thus, in the non-magnetic case with $B_0 = 0$ μG the cloud followed the typical star-forming evolutionary track. The same was the case, albeit on a slower time scale, for the cloud with $B_0 = 1.2$ μG. For larger B_0 (= 1.3 μG), the cloud followed the non-star-forming track. The reversal of the gravitational collapse in this case was the

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result of the increase in the magnetic pressure gradient force acting outward. The magnetic pressure gradient force increased because the magnetic field in the core increased, in response to the increase in the core density, according to the assumed scaling law for the field strength.

4. Important Implications

The possibility of the reversal of the gravitational collapse in the model clouds has important ramifications. Generally, gravitationally contracting cloud cores are thought to be a rarity, because their common occurrence are interpreted as leading to star formation rate in excess of the observed. Cloud cores were, therefore, thought to be in near equilibrium. These general believes could now reverse, because gravitationally evolving clouds may not always form stars. Most of the time they may be on non-star-forming evolutionary tracks. As a corollary, it appears possible that cloud cores in dynamical equilibrium may be exception rather than the norm.

The reversal of gravitational collapse after the formation of a dense core is equivalent to a mechanism for dissipating dense cores and cycling of interstellar gas between dense and diffuse phases. Shocks and winds from nascent stars may also disperse dense cores (Williams 1986, 1987). These mechanisms are, however, clearly limited to cores in the vicinity of active star formation. In contrast, the dissipation of dense cores through the reversal of gravitational contraction has the potential to be effective in both star forming and quiescent regions.

Possible conflict with the observed star formation rate having been eliminated, dynamically evolving clouds now seem to be a viable (or, perhaps the preferred) explanation for why the "early-time" molecular abundances from classical (pseudo time-dependent) models appear to agree with the observations better than the abundances predicted for the "late-time" near equilibrium conditions. The dynamically evolving models have the property that the time spent at any given core density decreases as the density increases. This property is clearly seen in the Figures 1 and 2. It introduces characteristic times that limit the time available to chemistry for equilibrating at any given high density. The explanation in terms of turbulent circulation currents is at best empirical at the present, and wind driven processes may operate in star forming region only.

By virtue of these positive attributes, dynamically evolving clouds become serious alternatives to cores in dynamical equilibrium. It is, therefore, imperative to examine the very basics of the two models in order to determine the reality.

5. The Search for Reality

At present the foundations for believing in either the evolutionary or the equilibrium models of dense cloud cores are not firm. We will now outline the studies needed to elucidate the reality.

The equilibrium models have put great reliance on the approximate (noisy) obedience, by the cores, of the virial balance equations ($\sigma^2 \simeq GM/R$) and Larson's relations ($\sigma \simeq R^{0.5}$ and $n \simeq R^{-1}$). While these relations have been used extensively, their utility as diagnostics of equilibrium has not been evaluated quantitatively. For example, a modeling study by Villere and Black (1982) suggests that gravitationally contracting clouds may also exhibit line shapes consistent with the observations. This study should be revived and extended to include clouds in dynamical equilibrium and the expanding phase of the dynamically evolving clouds. Villere and Black's (1982) studies were limited to CO lines. New studies should include lines of high density tracer molecules such as CS, and NH_3. Relations between σ, M/R, n and R exhibited by dynamically evolving model clouds can then be compared with those shown by model clouds in dynamical equilibrium for a proper diagnosis of the dynamical conditions in cloud cores.

Chemical diagnostic of the dynamical conditions in dense cores utilize the observed molecular abundances. Unfortunately, the abundances are not the primary observed quantities. They are the derived quantities. Astronomers observe only the line intensities and line profiles. Observed line intensities are then converted into abundances using simplifying assumptions about the excitations (e. g., LTE), radiative transfer (e. g., slab geometry), and physical-chemical conditions (e. g., uniformity in the emitting or absorbing region). This conventional practice suffers from serious drawbacks. The conditions of ambient density, temperatures and velocity field assumed by the observers in reducing their data may significantly differ from those in the theoretical models. Prasad et al (1990) have presented several examples of these differences which are dramatic for C_2 and C_2H. We need complete, end-to-end, mutually consistent, models to predict line intensities for comparison with the observational data. These models would start with the results of ab-initio chemical-dynamical or chemical equilibrium calculations. They should then proceed to statistical equilibrium calculations and end with radiative transfer calculations for the emergent line intensity and profiles for direct comparison with the primary observational data. Only then the molecular chemistry diagnostics of the dynamical conditions in the dense cores will be on a firm foundation.

6. Summary

Observed molecular abundances and chemical dynamical modeling results suggest that dense cloud cores may not be in equilibrium. Instead, they may be dynamically evolving in such a manner that the time spent at high densities decreases as the density increases. After attaining a high density, a gravitationally contracting core may either expand to states of lower core densities or may proceed to star formation. Cloud mass and initial density constitute some of the factors that affect the evolutionary track. Mutually consistent end-to-end modeling of the spectral line intensities and profiles may have the potential to provide the data needed to discern the reality.

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