THE INTERACTION OF T-TAURI STARS WITH MOLECULAR CLOUDS

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Winds from T-Tauri stars may provide an important dynamical input into cold molecular clouds. If the frequency of T-Tauri stars exceeds 20 pc^{-3}, wind-driven shells collide and form ram pressure confined clumps. The supersonic clump motions can account for cloud line widths. Clumps collide inelastically, coalescing and eventually becoming Jeans unstable. For characteristic dark cloud temperatures low mass stars form, and we speculate that in this manner clouds can be self-sustaining for 10^7 - 10^8 yr. Only when either the gas supply is exhausted or an external trigger stimulates massive star formation (for example, by heating the cloud or enhancing the clump collision rate), will the cloud eventually be disrupted. A natural consequence of this model is that dark cloud lifetimes are identified with the duration of low mass star formation, inferred to exceed 10^7 yr from studies of nearby star clusters. Other implications include the prediction of the existence of embedded low mass stars in turbulent cloud cores, the presence of an internal source of radiation in dark clouds, and a clumpy structure for cold molecular clouds.

I. INTRODUCTION

A long-standing problem with molecular clouds lies in understanding their characteristic line widths. On all scales that have hitherto been mapped, the line widths are highly supersonic, although there is some indication that on sufficiently small scales they may not be much broader than thermal (Myers *et al.* 1978). It is evident that simple uniform collapse or expansion models cannot account for observed line widths. Such models imply short lifetimes ($\sim 10^6$ yr) and excessive star formation rates (Zuckerman and Evans 1974). Moreover, recent radiative transfer analyses of molecular line profiles suggest that large scale velocity gradient models are too simplistic (Kwan 1978; Linke and Goldsmith 1979).

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We wish to present here a new proposal for providing input of stellar energy into these cold, molecular clouds which in general are observed to be bound. It should be noticed that a considerable fraction of the molecular gas (∿ 90% according to Rowan-Robinson 1979) is cold, i.e., $T_{CO} \lesssim 15$ K. We evidently cannot appeal to energy input associated with the interaction of embedded massive stars to account for the dynamical structure of cold molecular clouds.

We note first that the mean lifetime of molecular clouds may be estimated as follows. If Σ is the surface density ($M_\odot$ pc^{-2}) and S is the star formation rate ($M_\odot$ yr^{-1}), both evaluated at the same galactic radius, and ξ is the efficiency of star formation, the mean cloud lifetime = $\xi\Sigma/S$. In the solar neighborhood we adopt $\Sigma = 2M_\odot$ pc^{-2} and $S = 4 \times 10^{-9} M_\odot$ yr^{-1} pc^{-2} (Miller and Scalo 1979), and infer a mean cloud lifetime of 5×10^7 (ξ/0.1) yr. A star formation efficiency of $\xi \sim$ 0.05-0.1 is indicated by recent studies of dark clouds (Cohen and Kuhi 1979). Comparison of the CO distribution with that of OB associations yields a post-density wave shock lifetime of ∿ (3-4) × 10^7 yr (Bash, Green, and Peters 1977). These lifetime estimates greatly exceed cloud free-fall times, and show that it is necessary to consider a means of stabilizing clouds against collapse.

Supersonic turbulence will rapidly dissipate. It is evident that in order to maintain the dynamical motions implied by molecular linewidths, either an external or an internal source of momentum must be considered. A review of the problems associated with various possible mechanisms for stabilizing clouds has been given by Field (1978), who suggested that rotation is the principal stabilization mechanism. Mouschovias (1978) has argued in favor of magnetic stabilization. However, detailed observations of molecular clouds provide no evidence for sufficient rotation to stabilize clouds. Also, recent Zeeman-splitting observations strongly constrain the role of magnetic fields in dense clouds. We therefore wish to assert that the most plausible stabilization mechanism is the interaction of embedded stars with molecular clouds. In a later paper, we discuss the interactions of massive stars with warm molecular clouds (Norman and Silk 1979a). Here we consider cold molecular clouds, where only low mass stars can be present. Low mass stars may provide an important dynamical interaction with the surrounding medium during their pre-main sequence convective phase. During much of this time, which lasts ∿ 2 × 10^7 yr for a star of 0.8 $M_\odot$, these stars are believed to be in the T-Tauri phase. The T-Tauri phenomenon is characterized by extensive mass outflow (and possibly inflow; Ulrich 1976). Characteristic outflow velocities are 100-300 km s^{-1} at mass flow rates of 10^{-7}- 10^{-8} $M_\odot$ yr^{-1} (Kuhi 1964).

Let us first ascertain whether the momentum input from T-Tauri winds can provide a significant contribution to molecular cloud dynamics. Since momentum is approximately conserved during the interaction of these radiatively cooled winds with the ambient cloud material, a rough estimate of the resulting velocity dispersion transmitted to an average volume element of cloud material is

$$\langle\Delta v\rangle \sim \left(\frac{M_*}{M_{cl}}\right)\left(\frac{\dot{m}t_{T\text{-}Tauri}}{m}\right) V_w$$

where M_* is the stellar mass in the cloud, M_{cl} is the cloud mass, $\dot{m}$ is the mean mass loss rate of an individual T-Tauri star of mass m over time $t_{T\text{-}Tauri}$, and V_w is the wind velocity. Adopting $M_*/M_{cl} \sim 0.1$ (Cohen and Kuhi 1979), we conclude that if a fraction ~ 0.1 of the initial stellar mass is lost in the pre-main sequence phase, then $\langle\Delta v\rangle \sim (1\text{-}3)$ km s^{-1}.

This demonstrates that T-Tauri stars could provide significant dynamical input into molecular clouds. To pursue this idea further, we now consider in more detail the nature of this interaction between T-Tauri stellar winds and the ambient molecular cloud.

II. WINDS, BUBBLES, AND SHELLS

Once the mass swept out by the T-Tauri winds exceeds the ejected mass, a strong shock develops which rapidly forms a shell that subsequently snowplows into the molecular cloud. The subsequent evolution of the approximately momentum-conserving shell resembles that of interstellar bubbles (Weaver *et al.* 1977). One notable difference is that for wind velocities $\lesssim 100$ km s^{-1} the wind will be strongly radiative. Details of T-Tauri bubble evolution are given by Norman and Silk (1979b). The most relevant question that concerns us here is the extent of the bubble and shell radius, R_s. Norman and Silk show that

$$R_s = \left(\frac{\dot{M}V_w}{4\pi\rho V_*^2}\right)^{1/2}$$

$$= 0.1\left(\frac{\dot{M}}{10^{-7}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{V_w}{100\ \mathrm{km\ s}^{-1}}\right)^{1/2}\left(\frac{n}{10^3\ \mathrm{cm}^{-2}}\right)^{-1/2}\left(\frac{V_*}{1\ \mathrm{km\ s}^{-1}}\right)^{-1}\mathrm{pc}.$$

The limiting radius is reached when the ram pressure due to the motion of the stars, V_*, through the cloud balances the wind momentum. The swept-up mass at this stage amounts to $\sim 1\ M_\odot$.

Consider next the question of how many low mass T-Tauri stars are required in order for the shells to collide. If the T-Tauri star density n_T is sufficient for shell collisions to prevail, then the molecular cloud will effectively develop a 2-phase medium consisting of dense swept-up shells moving in a more diffuse medium. The shell-shell collision time is of order $(n_T\pi R_s^2V_*)^{-1}$, and the necessary condition is that this be less than $t_{T\text{-}Tauri}$. Adopting $t_{T\text{-}Tauri} = 0.1\ m/\dot{m}$ as before, we infer a critical density of T-Tauri stars of order

$$20\left(\frac{V_*}{1\ \mathrm{km\ s}^{-1}}\right)\left(\frac{n}{10^3\ \mathrm{cm}^{-3}}\right)\left(\frac{100\ \mathrm{km\ s}^{-1}}{V_w}\right)\mathrm{pc}^{-3}.$$

This is equivalent to requiring the stellar mass fraction in the cloud to exceed $\sim 0.1\ (V_*/1\ \mathrm{km\ s^{-1}})(100\ \mathrm{km\ s^{-1}}/V_w)$.

It is of interest to compare the T-Tauri star density with available data. The best studied dark cloud region is the Taurus-Auriga dark cloud complex. According to Cohen and Kuhi (1979), the considerable number of T-Tauri stars distributed in the outer regions of dark clouds occur in aggregations that range up to densities of $\sim 30\ \mathrm{pc^{-3}}$. Jones and Herbig (1979) cite a lower number ($\sim 4\ \mathrm{pc^{-3}}$) for aggregations in the same region. We should bear in mind that the maximum A_V for the T-Tauri stars in the Cohen and Kuhi sample is $A_V \sim 4$, and the T-Tauri star density could be greater in the denser cloud core regions. According to Jones and Herbig (1979), the proper motions of the T-Tauri stars indicate a velocity dispersion of 2-3 km $\mathrm{s^{-1}}$. Again, we remark that this value of V_* refers to the outer regions of the dark clouds.

It is evident that these values of V_*, V_w, and n_T are indicative that T-Tauri stellar winds could indeed drive shells that collide in dark clouds similar to the clouds in the Taurus region. One consequence of this hypothesis that supersonic line widths especially in dark cloud cores find a ready explanation in continuously driven turbulence. The interacting shells will build up into clumps of dimension ~ 0.1 pc and mass ~ 0.1-$1\ M_\odot$. These will only be weakly confined by ram pressure because of their low Mach numbers, and are likely to continuously replenish the interclump medium. Thus we envisage that cloud cores will contain many wind-driven clumps. Clumps of lower column density will be driven out of the cloud cores by the winds, and consequently the lower density outer parts of clouds may be undergoing more systematic large-scale motion. This could either be inflow, if the cloud cores are accreting material from the larger, more diffuse molecular cloud complex in which they are embedded, or outflow, if interacting winds from the core can drive large-scale motions. One might speculate that cycles of inflow and outflow could alternate, being regulated, as we now argue, by low mass star formation.

III. LOW MASS STAR FORMATION

We have indicated a means of explaining cold cloud line widths. However it is also necessary for the clouds to be sufficiently long-lived. Longevity and stability require continuous low mass star formation, and we now speculate on a mechanism for achieving this.

For temperatures characteristic of clumps, the Jeans mass equals $10(T/10\mathrm{K})^{3/2}(10^4\mathrm{cm^{-3}}/n)^{1/2}\ M_\odot$. We argue elsewhere that inelastic clump collisions and clump coagulation will dominate over competing processes such as leakage and acceleration. Thus, within a few clump-clump collision times or $\sim 10^7$ yr, the clumps will become Jeans unstable and form low mass stars. It seems unlikely that massive stars could be formed unless an external heat source is supplied to raise the Jeans mass above $\sim 1\ M_\odot$.

This leads us to the following model. Low mass stars will form, and develop winds which sweep up shells. The shells intersect, break up into clumps that are driven together by the winds, gradually coalescing and eventually forming low mass stars. Thus, low mass star formation is self-sustaining, and proceeds continuously either until the gas supply is exhausted or an external trigger stimulates disruptive massive star formation. For example, we envisage that interaction with a nearby OB star association would provide sufficient energy input to raise the Jeans mass and enhance the coagulation rate sufficiently to enable massive stars to form. One important piece of evidence is the fact that studies of star formation indicate that star formation is non-coeval (Herbig 1962). Low mass star formation has evidently been occurring over a timescale in excess of $\sim 10^7$ yr. Then *our star formation model identifies the timescales associated with cold molecular clouds and non-coeval star formation, and incorporates both into a unified model.* Both problems can be simultaneously resolved in our picture.

IV. IMPLICATIONS

If cold molecular clouds are supported by interactions of winds from embedded T-Tauri stars, there are a number of observable consequences. Typical T-Tauri bolometric luminosities are $\sim$ 1-10 $L_\odot$. Moderate improvements in sensitivity of far IR surveys of dark clouds should be capable of testing our hypothesis, particularly if diagnostics specific to T-Tauri stars can be utilized. Specifically, these could include far infrared line emission from fine-structure excitation of CI and OI, and H_2 vibrational lines associated with the shocked gas.

There are also significant consequences for molecular cloud observations. There will be an internal source of UV due to wind shocks equivalent to the mean interstellar radiation field at a visual extinction of $A_V \sim 3$. This could result in significant modification of dark cloud chemistry by means of photo-dissociation of molecules and photo-ejection both of molecules and electrons from grain surfaces.

Typical density contrasts expected amount to a factor ~ 10, with a volume filling factor ~ 0.1 and a clump scale of ~ 0.1 pc. The ram-pressure confined clumps satisfy $n \propto v^2$, and the gas that contributes to emission line wings may therefore be denser than gas contributing to the line cores. The implications of our model for detailed line profiles remain to be explored. However, the basic feature of our model, namely a turbulent clumpy core surrounded by a more extensive, diffuse halo region sustaining a relatively uniform inflow or outflow, are consistent with recent models for molecular line profiles.

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DISCUSSION FOLLOWING SILK

Gilmore: You are using your model to account for the stability of all clouds. However Zuckerman and Evans estimated that if all clouds formed stars, then the rate of star formation would be 10-100 times greater than observed. Can your model be consistent with their estimate?

Silk: Unacceptably high star formation rates arise only if molecular clouds are assumed to have short lifetimes comparable to the free-fall time-scales. We are proposing that the clouds are stabilized by star formation over a time-scale of order a few tens of millions of years with an efficiency of order 10%. The corresponding mean star formation rate is then of order 0.1 x (mass in molecular clouds)/cloud lifetime, or a few solar masses per year, consistent with the observed rates.

Mezger: There is a severe problem with your proposed model if it is to work in giant molecular clouds: the star formation rate in the Galaxy is $\sim 3\ M_\odot\ yr^{-1}$. An upper limit for the age of the T-Tauri stage of low mass stars is $\sim 10^6$ yr. It follows that there are some 10^6 T-Tauri stars in the Galaxy, or some 100 per giant molecular cloud. This number falls orders of magnitude below what your model requires.

Silk: My estimates of T-Tauri stars needed and likely to be present differ from yours. First, what does the model require? To provide efficient stirring up of, say, $10^9\ M_\odot$ in cold molecular cloud cores requires $\sim 10^8$ T-Tauri stars in the galaxy. How many are present?

The observed star formation rate of $\sim 3 M_{\odot}$ yr^{-1} implies that ~ 4 yr^{-1} is the formation rate of low mass stars (mean mass 0.8 $M_{\odot}$, say) and therefore is also the approximate formation rate of T-Tauri stars. If the lifetime of the T-Tauri phase is even 10% of the duration of the pre-main sequence convective phase ($\sim 2 \times 10^{7}$ yr for a star of 0.8 $M_{\odot}$), there must be $\sim 10^{7}$ T-Tauri stars present in the galaxy at any time. The stellar winds from these stars suffice to stir up $\sim 10^{8}$ $M_{\odot}$ of gas, perhaps enough to account for a significant fraction of the cold molecular cloud cores that show evidence for turbulent line broadening. Because of uncertainties in the mass-range of T-Tauri stars, the duration of their outflow phase, and the initial stellar mass function, it seems not unlikely that up to $\sim 10^{9}$ $M_{\odot}$ of molecular cloud gas could be affected by T-Tauri stellar winds.

Bok: Can Herbig-Haro Objects take the place of T-Tauri stars? We now have one globule near the edge of the Gum Nebula which shows two Herbig-Haro objects being ejected at high speed.

Silk: It is indeed possible that Herbig-Haro objects could provide significant heating in dense clouds and globules. Acting much like "interstellar bullets," I believe they could penetrate distances up to ~ 1 parsec.

Zuckerman: Strong stellar winds from T-Tauri stars are required for your model, but their existence has been disputed by Ulrich and Knapp. Also, the IRAS satellite scheduled for launch in 1981 will be capable of detecting, in the infrared, the embedded stars required in your model.

Silk: I agree.

Myers: Earlier in the symposium we heard that there are "clumps" in the Taurus complex which have size about 0.1 pc, mass about 1 $M_{\odot}$, and which appear to have significant density contrast. These parameters appear consistent with your model. However we have noticed that the linewidths are extremely small, only about 2 or 3 times the thermal width. Are these widths consistent with your model?

Silk: Such narrow linewidths would imply mildly supersonic motions for the clumps. In our model, these motions lead to some degree of ram pressure confinement, with density contrast of order 10.

Kutner: For a simple spherical cloud with a small number of T-Tauri stars inside, how would you expect the observed linewidth to vary as a function of the distance of the line of sight from the centre of the cloud?

Silk: Our model suggests the existence of many clumps, with the more slowly moving clumps confined to the cloud core. Thus I would expect beam-to-beam variations (if a beam corresponding to ~ 0.1 pc resolution is used) in velocity structure, with smaller linewidths contributed from the core material than from the cloud material. However ram pressure confinement means that the gas contributing to the line wings could be denser than the lower velocity gas, so there might be significant opacity in the line wings. This effect complicates predictions of linewidth variations.

Mouschovias: What fraction of molecular clouds contains sufficient T-Tauri stars for your mechanism to work? If polarization observations show large-scale ordering of the magnetic field, would that not be an embarrassment to every model appealing to disordered gas motions in dense clouds?

Silk: Observations of T-Tauri stars have been made only in the outer fringes of a few nearby dark clouds. The observed frequency indicates that T-Tauri stars could be sufficiently common in core regions for our model to work. Polarization observations of embedded infrared sources could indeed provide significant information on the large-scale structure of the field. If large-scale ordering could be unambiguously demonstrated, it would suggest that magnetic forces play a major role in the cloud structure.