GENERAL PHYSICAL CHARACTERISTICS OF THE INTERSTELLAR MOLECULAR GAS

B. E. Turner
National Radio Astronomy Observatory*
Green Bank, West Virginia, U.S.A.

The interstellar medium may be characterized by several physically rather distinct regimes: coronal gas, intercloud gas, diffuse clouds, isolated dark clouds and globules (of small to modest mass), more massive molecular clouds containing OB (and later) stars, and giant molecular clouds. Molecules first appear in the denser diffuse clouds, and occur everywhere that $A_V \gtrsim 1^m$. Values of temperature, density, ionization fraction, mass, size, and velocity field are discussed for each regime. Heating and cooling mechanisms are reviewed. Nearly all molecular clouds exceed the Jeans criteria for gravitational instability, yet detailed models reveal no cases where observations can be interpreted unambiguously in terms of rapid collapse. The possibility that clouds are supported by turbulence, rotation, or magnetic fields is discussed, and it is concluded that none of these agencies suffice. Comments are made about fragmentation and star formation in molecular clouds, with possible explanations for why only low mass stars form in low mass clouds, why early-type stars form only in clouds with masses $\gtrsim 10^3$ $M_\odot$, and why O-stars seem to form near edges of clouds. Finally, large-scale interactions between molecular clouds and the galactic disk stellar population are discussed.

I. MORPHOLOGY OF THE INTERSTELLAR MEDIUM

Although the range of physical parameters characterizing the interstellar medium may well form a continuum of values, it is convenient (and present observations permit us) to describe the interstellar medium in terms of a few, rather distinct regions.

1) "coronal" gas refers to a hot, diffuse component revealed by absorption lines of atoms in high stages of ionization seen in the far-UV spectra of OB stars; the most conspicuous of these is the O VI ion, whose abundance reaches a peak in the temperature range $5.3 \leq \log T \leq 5.9$ which, along with $-2.3 \leq \log n \leq -1.5$, characterizes these regions (Jenkins, 1978a,b). The filling factor for coronal gas is 0.2 to 0.5 (Myers 1978) and the pressure in these regions is $p/k \lesssim 10^4$ cm^{-3} K.

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2) intercloud gas is seen in the form of broad, low-intensity emission features in the 21-cm spectra of HI observed toward extragalactic sources at high latitudes (Davies and Cummings 1975; Lazareff 1975). This gas is somewhat cooler ($2.9 \leq \log T \leq 4$) and denser ($-1.0 \leq \log n \leq 0$) than the coronal gas, although the current observations are insensitive to gas hotter than $\sim 10^4$ K. This gas is well described by a pressure $p/k = nT \simeq 10^3$ cm^{-3} K.

3) diffuse interstellar clouds are defined here as those with $2(19) \leq N \leq 2(21)$ cm^{-2}, where $N = N_H + 2N_{H_2}$, the total column density, is inversely correlated with temperature: $\log N = a - b \log T$. The lower limit on N is the currently lowest detectable value (by 21-cm absorption techniques; Davies and Cummings 1975; Lazareff 1975), while the upper limit on N represents the value above which T becomes roughly independent of density (A_V becomes $>1^m$ and the UV field becomes unimportant). At the low-N range, these clouds have no molecular content, while the higher-N clouds have appreciable amounts of H_2, observed optically (Spitzer and Jenkins 1975; Savage et al. 1977), and CO, observed at λ2.6 mm (Knapp and Jura 1976). The distribution in sizes, based on statistical analyses of selective extinction, indicates two groups of clouds: large ones with radii $\sim$35 pc, and "standard" ones with radii of $\sim$5 pc (Spitzer 1978). The latter, $\sim$8 times more numerous, are characterized in Table 1. Direct measures of a few cloud sizes have been made by Greisen (1973, 1976). A representative pressure for these clouds is $p/k \simeq 3700$ cm^{-3} K, although some are much lower.

4) "isolated" dark clouds refer to well-defined regions of extinction, $\sim 1 \leq A_V \leq 25^m$ (the upper value representing the limit of star-count techniques) which are not associated with emission or reflection nebulosity (i.e., regions containing early-type stars). These clouds are largely, if not completely, molecular, except for possibly a shell of HI around the larger ones. The temperature is nearly always 10 ± 3 K, and the linewidths are much more constant over these clouds than over other cloud types. While the parameters in Table 1 characterize these clouds as a whole, several of them are now recognized to contain denser cores ($n \sim 10^4$ cm^{-3}) not related to the presence of embedded stars.

5) "large" globules as defined by Bok et al. (1971) and Bok (1977) have recently been found from molecular studies (Dickman 1976; Martin and Barrett 1978) to have densities and temperatures very similar to the denser isolated dark clouds. The mass and size distributions of these globules seem to fit onto the lower end of the corresponding isolated dark cloud distributions. Bok (1977) estimates there are 25,000 large globules in the galaxy.

6) dark clouds associated with AB star formation have long been recognized by the presence of emission or reflection nebulosity associated with the obscured regions. CO maps of these regions have shown that the attendant dark clouds are statistically larger and more massive than the isolated dark clouds, and that, as expected, sizable regions of enhanced temperature and density accompany the locations of embedded stars or shock fronts. As judged from linewidths, these clouds are generally more quiescent than those associated with O star formation.

7) molecular clouds associated with O star formation are discussed here as a separate category because it is often felt that they are larger and more massive than other clouds. While the two or three most massive clouds known do contain O stars, the mass distributions of categories 6) and 7) almost completely overlap; some clouds with O stars are smaller than some clouds with only later-type stars.

8) molecular cores in clouds forming A,B,O stars do not appear to show a wide range of masses or sizes. While parameters describing cores are subject to large uncertainties of selection (e.g., limited spatial resolution) and of definition, it does appear that no great distinction can be made between cores associated with regions of O stars, and later-type stars.

9) giant molecular clouds have recently been mapped in many regions, primarily with the Columbia and Texas telescopes, and include the prominent examples M17 (Elmegreen 1977), Cep OB3 (Sargent 1977), Sgr B2 (Scoville et al. 1975), Orion (Kutner et al. 1977), W49 (Mufson and Liszt 1977), Ser OB1 (Elmegreen and Lada 1976), Cyg OB1, Cyg OB2, Cyg OB8, Cyg OB9 (Cong 1977), Cas OB6, IC1848/W3 (Lada et al. 1978), Per OB2, Gem OB1 (Baran 1978), and Mon OB1, Mon OB2, CMa OB1 (Blitz 1978). A clear-cut definition of a giant cloud is not presently possible, as the edges of many of them are defined by observational sensitivity, and because some giant clouds have recently been found to merge with others (e.g., Orion-Monoceros, Taurus-Perseus clouds). A tentative definition is $L > 30$ pc in one dimension, $M > 5(4)\ M_\odot$. Recent survey work of Scoville and Solomon (this volume) finds the galaxy containing ∿4000 such clouds. A rather general cutoff in size and mass seems to be $L \sim 100$ pc, $M \sim 3(5)\ M_\odot$, probably as a result of tidal disruption caused by the differential rotation of the galaxy (Stark and Blitz 1978). (Note, however, that M17 has $L \simeq 170$ pc in one direction.) These clouds are often quite elongated and the majority of them seem to be oriented roughly parallel to the galactic plane. All giant clouds studied so far contain or are associated with regions of early-type star formation (a selection effect: see e.g., Blitz 1978b). As might be expected, the non-core component of giant clouds, comprising virtually all of the volume and mass, consists of gas similar in properties to that of dark clouds, or even diffuse clouds at the outer regions.

These categories of the molecular gas are phenomenological only. The next steps are to quantify the properties of these classes, and then to seek physical explanations.

II. PHYSICAL PROPERTIES OF THE MOLECULAR MORPHOLOGICAL COMPONENTS

The above categories divide rather naturally into the low-pressure (coronal, intercloud, and diffuse cloud) components, and the high-pressure (various molecular) components of the interstellar medium. Methods for determining T and n have been described by Myers (1978).

The low-pressure components are not the subject of this review, and we will only remark on them briefly. They are usually assumed to be in pressure-equilibrium (although there may be significant pressure differences between coronal and intercloud components), and the pressure may be taken as ~ 3700 cm^{-3} K, as predicted by McKee and Ostriker (1977; "MO") in their recent 4-component model of the interstellar medium. With this assumption, Myers (1978) is able to derive filling factors of ~ 0.5 and 0.3 for coronal and intercloud components, respectively. The latter may be identified with MO's "warm ionized" plus "warm neutral" media.

Molecules make their appearance in the onset of the high-pressure components which clearly cannot be in pressure equilibrium with the interstellar medium as a whole. All categories of molecular components are gravitationally bound (the question of collapse is dealt with later) and, taken together, they correspond with the "cold neutral medium" of MO, who deduce a filling factor of $f \gtrsim 0.02$ for it. This factor is probably consistent with observations; Scoville and Solomon (1975) find $f \gtrsim 5(-3)$, a lower limit owing to incomplete sampling. Of course, the MO theory is not concerned with the details of the molecular component.

Table 1. Physical Properties

Type	T(K)		n (10^3 cm^{-3})		Mass ($\odot$)		Size (pc)	
	typical	range	typical	range	typical	range	mean	range
diffuse clouds	80	40-150	0.03	0.02-1.0	4(2)	?	5	$\lesssim$1 - ?
isolated dark clouds	10	6-15	1	0.2 -7.4	2.6(2)	˙5-1.3(3)	0.9	0.2-2.3
large globules	10	7-14	8	2.5 -14.	20	0.3-70	0.3	0.1-1.1
dark clouds + AB stars	see text		see text		1(4)	2.5(2)-7.6(5)	8	1-60
mol. clouds + O stars	see text		see text		2(4)	1.5(3)-2.5(6)	30	3-170
molecular cores	36	20-150	40	3-1(3)	1(3)	1(2)-5(4)	1	0.2-5.4
giant molecular clouds	see text		see text		$\geq$1(5)	7(4)-2.5(6)	60	30-170

Table 1 gives the physical properties of the molecular components. Several points should be noted.

1) Masses are estimated from observations of ^{13}CO, using the relation $^{13}CO/H_2 = 2(-6)$ or $CO/H_2 = 8(-5)$ (Dickman 1976). This relation has been questioned. Leung and Liszt (1976) find $CO/H_2 \gtrsim 3(-5)$ for warm ($T \gtrsim 40$ K) clouds, and $\sim 1(-5)$ for cold ($T \gtrsim 15$ K) clouds. Wootten <u>et al</u> (1978) find $CO/H_2 = 4(-6)$ in warm clouds, 2(-5) in cold clouds. Guélin <u>et al</u>. (1977) and Turner and Zuckerman (1978) find $CO/H_2 \leq 3(-6)$ in certain cold clouds, but this result is not necessarily general. Thus CO/H_2 should possibly be reduced from Dickman's value by 3 to 20 times in warm clouds, and ~ 4 times in cold clouds. In addition, LTE analyses, used here, may underestimate or overestimate N(CO) depending on n and T; probably (Leung and Liszt 1976) N(CO) is overestimated by factors of ~ 1.5 in warm clouds and ~ 4 in cold clouds. Thus the above masses for the warmer sources may need revision upward by a factor of 2 to 13 times

2) There is an almost complete overlap in the mass distribution of dark clouds with associated AB stars, and molecular clouds with O stars. On the other hand, the mass distribution of these two categories shows only a small overlap with the mass distributions of the lighter isolated dark clouds and large globules. (These latter two categories have highly overlapped mass distributions also, although the lowest-mass objects tend to be globules). Thus it appears that a threshold mass, ∿1000 $M_\odot$, is required before ABO star formation can occur, and that once this mass is attained, O-stars and AB stars may both form, although far fewer such clouds contain O stars.

3) For dark clouds with AB stars, T and n range from $\leq$ 10 K and $\leq$ 1(3) cm^{-3} at the outer extremities to values characterizing the cores, namely, $25 \leq T \leq 50$ K and $5(3) \leq n \leq 5(4)$. Many of these clouds are small enough that the cores noticeably heat the entire cloud, over its presently mapped extent. For molecular clouds with O stars the same remarks apply except that the most intense cores have values of T up to $\gtrsim$ 100 K and n up to 1(6) cm^{-3}. These values are defined as averages over a 1' beam and therefore involve selection effects. The presence of masers indicates densities as high as 1(9) cm^{-3} in some cores.

4) For dark clouds with AB stars, Knapp et al. (1977) find observationally that the presence of ∿A0 to B0 stars is a necessary but not sufficient condition for heating of the molecular gas over even a small region ($\gtrsim$ 1') readily detectable with current instrumental resolutions. On the other hand, some clouds are known to be significantly heated over extensive regions by B stars (e.g., ∿3 pc in S255; Evans et al. 1977). O stars always reveal their presence by heating extensive volumes of molecular clouds, although in cases where the core density is not high, the temperature increase may be less than for several B-star cores.

5) Velocity widths of the molecular gas appear to be indicators of both the presence of stars or protostars, and of their type. For isolated dark clouds, Dickman (1975) finds widths of 2.5 ± 2 km/s. For dark clouds with AB stars, the distribution in widths peaks at 2.5 km/s but has a tail out to values of ∿10 km/s, arising in the core regions; however the majority of cases show values typical of isolated dark clouds. For molecular clouds with O stars, line profiles are often much wider and of complex shape, variously indicating core rotation (Ori (KL)) multiple core components (W51, W49, Sgr B2?), a high degree of unspecified "turbulent" motion (M17, M8), or mass flow (Ori (KL)). The question whether enhanced velocity widths are also indicative of collapse near molecular cores is controversial (see below). The best case for collapse is probably made for globules (Martin and Barrett 1978), but this does not obviously apply to other types of clouds.

Fractional ionization are: 2(-4) to 1(-3) for diffuse clouds, $\leq$ 1(-8) but >3(-10) for most dark clouds and dense molecular cores, and 3(-10) to 1(-9) for some isolated dark cloud cores with enhanced deuterium fractionation.

III. HEATING AND COOLING OF MOLECULAR CLOUDS

1) *Diffuse Clouds* (Jura 1978) are cooled by collisional excitation of the fine structure levels of C^+, whose fractional abundance according to Copernicus observations ranges from 4(-5) to 4(-4) depending on the type of determination. If $T > 100$ K, rotational levels of H_2 also become important. Heating by cosmic rays is inadequate, even if the ionization rate ζ_o is as high as 1(-16) $\sec^{-1}$, which appears unlikely. Starlight seems to be the only viable heat source. Energy released by the photodissociation of H_2 (and its reformation) is probably insufficient, but continuum absorption of starlight by grains, with the attendant photo-ejection of electrons, probably suffices especially if the grains are rather small. A combination of cooling by C^+ and heating by photo effect on grains leads to an expected $T \propto n^{-1}$ dependence, which is consistent with observations and with the hypothesis of constant pressure for all diffuse clouds (i.e., pressure equilibrium). If the grain photo effect indeed dominates heating, then a minimum mass for clouds to become self-gravitating (against thermal pressure) can be estimated as a function of the external intercloud pressure. Jura (1976) finds critical masses of 10^2 - 10^4 $M_\odot$ depending on several uncertainties.

2) *Isolated Dark Clouds*, along with the outer regions of star-containing clouds, have a well defined temperature, $T \approx 10 \pm 3$ K, apparently independent of density over the range $1(2) \lesssim n \lesssim 3(3)$. Cooling is via collisional excitation of CO rotational transitions (cooling by grains is unimportant at these densities). Heating by starlight is negligible owing to the large attenuation. Heating by cosmic rays, by gravitational collapse, and by ion-slip (ambipolar diffusion) are all possible (Myers 1978) in the formal sense that they fit the observed T *vs* n relationship within rather sizable uncertainties. However gravitational collapse is not favored because there is generally no evidence for it in the observed lineshapes, and because the fraction α of gravitational potential energy loss rate that must go into heating (0.3) is much higher than the expected fraction (0.02) corresponding to uniform compression. Ion-slip heating requires magnetic field strengths of $\gtrsim 100$ μG, probably not consistent with current observed upper limits in two of these clouds (Crutcher *et al*. 1975). The required fields would marginally offer support against gravitational collapse. However, the cosmic-ray heating model probably best fits available data.

The same picture applies to globules. Here, however, gravitational collapse appears inconsistent with observed line profiles according to detailed models of Leung and Liszt (1978).

3) *Clouds with stellar-type sources* here include clouds associated with A, B, and O stars, HII regions, and protostars. Outside the $T = 10$ K contours of these clouds, the processes described for isolated dark clouds apply. Inside these contours the same heating processes (except cosmic rays) operate, in addition to heating by the embedded or adjacent stellar/protostellar sources. Within the 10 K contours, the observed narrow range of $T_B(^{12}CO)/T_B(^{13}CO)$ implies $T \propto N(^{13}CO)^p$ with $p \approx 0.2$ to 0.3 (Myers 1978). Also, with more scatter, $T \propto n^p$. In the presence of CO as the dominant coolant, heating solely by gravitational collapse

yields the observed (T,n) relation only for $\alpha \approx 0.3$ and $M \approx 1(5)\ M_\odot$. Again, this process is not to be favored, as α is much higher than the value 0.01 corresponding to uniform compression, and because many warm clouds do not have $1(5) M_\odot$. Ion-slip heating appears satisfactory except for the hottest core regions. (A magnetic field strength of $\sim 270\ \mu$G is required (Myers 1978), comparable with present relevant observational limits.) In these cores, or anywhere that $n \gtrsim 10^4 - 10^5\ \mathrm{cm}^{-3}$, gas collisions with warm grains will dominate the heating. For the specific grain-heating model given by Goldsmith and Langer (1978) the slope of the (T,n) relation is predicted as ~ 0.3 for $n = 10^4 - 10^5\ \mathrm{cm}^{-3}$ (in agreement with observations) and ~ 0.5 for $n = 10^3 - 10^4\ \mathrm{cm}^{-3}$. A grain temperature $T_{gr} \gtrsim 100$ K is needed for most sources, and ~ 200 K for a few particularly hot cores. $T \approx 0.5\ T_{gr}$ at $n = 10^5\ \mathrm{cm}^{-3}$. A rather simpler model by Knapp et al. (1977) also provides satisfactory agreement with observations of warm cores in clouds heated by B0 and later stars. The observed fact that A0 stars are necessary but not sufficient to heat cores above 10 K is explained in terms of a threshold density of $\sim 5(3)\ \mathrm{cm}^{-3}$. A detailed model of the S255 molecular cloud (Evans et al. 1977) shows that three B0 stars at the cloud edge are able to heat all of the 7 x 2 pc region ($M \sim 4(3) M_\odot$) that lies above 10 K. By contrast, Blair et al. (1978) find that a corresponding 6 x 3 pc region in the S140 cloud cannot be entirely heated by two nearby B0 stars plus an embedded IR source (latent B0 star); heating mechanisms other than heated grains are required here, although the core region is adequately heated in this way by the IR source. The unusually hot cores and extended warm regions associated with many O-star molecular clouds seem readily explained by the observed high grain temperatures and unusually high gas densities (e.g., Orion: Harvey et al. 1974; Werner et al. 1974).

In this section we have omitted several other possible heating mechanisms for molecular clouds, including conversion of differential rotation via magnetic fields (Hartquist 1977), chemical heating (Dalgarno and Oppenheimer 1974), and hydromagnetic waves (Arons and Max 1975). All of these appear inadequate.

IV. THE ENERGETICS AND EVOLUTION OF MOLECULAR CLOUDS

Are molecular clouds collapsing, or are they quasi-static? What is the nature of the fragmentation of clouds prior to star formation? What determines whether massive (O) stars form, as distinct from only B-type or later stars? We touch briefly on these presently unresolved questions.

A. Conditions in Collapsing Clouds

Obviously clouds both collapse and fragment since stars exist. Furthermore, the critical Jeans mass for gravitational instability is exceeded by all clouds except diffuse ones and a few of the smallest dark clouds and globules. The question is whether any clouds contract in a free-fall mode, or only much more slowly as a result of support by turbulence, magnetic fields, or rotation. If all clouds were free-falling, the rate of star formation would exceed the observed rate in the galaxy by a factor of 100 unless the efficiency of forming stars were only 1%; this seems unlikely based on recent studies of fragmentation (Larson 1978) and on observations (Vrba 1977) which indicate that the mass of stars formed is typically 10% of the parent cloud mass. Arguments in favor of free-fall collapse based on observed line profiles have been made for a few reasonably massive clouds (e.g., Loren 1977a,b; Snell and Loren 1977) and for several globules (Martin and Barrett 1978). However more detailed interpretation of these observations (Leung and Brown 1977; Leung and Liszt 1978) show that this conclusion is unwarranted. There appears to be no case at present of uncontroverted free-fall collapse.

According to Goldreich and Kwan (1974) turbulence cannot support clouds against rapid collapse because the required condition that the turbulent stress greatly exceed the thermal pressure (which gives negligible support) means that the turbulence must be supersonic. Then the turbulence will generate shock waves which can be shown to radiate away the shock energy in a time $\lesssim$ free-fall time. Hence turbulence at most increases the cloud lifetime against gravitational collapse by a factor of order unity.

Field (1978) has considered the possibility that rotation stabilizes clouds against collapse. Only a small minority of clouds so far studied via molecular lines can be interpreted as rotating. On the other hand, Hopper and Disney (1974, 1975) examined over 200 fairly compact dark clouds, many of which could be globules, and found that a significant fraction (44%) are elongated roughly parallel (within 30°) with the galactic plane (but not correlated with the magnetic field direction). Hopper and Disney believe that these clouds are probably disks, formed as a result of the gradient in gravitational force perpendicular to the galactic plane. Heiles (1976) suggests instead that these disks are rotating, and that they formed via rapid compression of diffuse clouds. The large-scale galactic magnetic field should keep diffuse clouds in corotation with the galaxy; this initial angular momentum, if conserved during compression to dark clouds, should correspond to a rotation of the latter of $\sim$1 km $s^{-1}pc^{-1}$, roughly what is necessary to rotationally stabilize them. Field points out that the thinner members of these disk-like objects are unstable to formation of bars, and that even bar-like clouds may be gravitationally unstable on a smaller scale. Examples of such clouds have probably been seen (Clark et al. 1977). To stabilize against such effects in most clouds, which do not show them, magnetic fields may be important. While the Hopper-Disney clouds have not been observed in molecular lines to test the rotation hypothesis, Heiles and Katz (1976) fail to observe rotation in several elongated dark clouds and conclude that their elongations arise from other factors. The fact that only three or four clouds of any type show signs of rotating with plane parallel to the galactic plane, as expected for this picture, suggests that rotation in general may not be a very important stabilizing effect.

The role of magnetic fields in molecular clouds is still speculative. Observationally, little is known about such fields in dense clouds. Heiles (1976) cites best values of a few μG and n $\sim$ 1 cm^{-3} for the general intercloud medium. If we scale $|B|$ by $n^{1/2}$as suggested by Mouschovias (1976), values of 10^{-4} to 10^{-3} gauss can be expected in dense clouds. Vrba et al. (1976) have demonstrated the presence of aligning fields in five dark clouds, but their magnitudes cannot be determined. Crutcher et al.'s (1975) upper limits for two dark clouds are 5(-5) gauss. As Field (1978) points out, magnetic fields do influence the distribution of gas on a large scale in the galaxy. But (amplified) magnetic fields may well diffuse out of molecular clouds in time scales short compared to their evolutionary times. This would not occur for diffuse clouds, but may well do so for the more highly condensed cloud types. For typical dark clouds, the diffusion time is only $t_d \overset{\sim}{\sim}$ 6(7). $[B/3(-6)\ \mu G]^{-2}$ yr for an ionization fraction of 1(-8) (Guélin et al. 1977). If the field has not diffused out, then radiation of Alfvén waves into the surrounding medium will brake the rotation of a cloud in a time which Field shows is less than the rotation period of the galaxy for diffuse clouds (thus they corotate with the galaxy); however for dark molecular clouds it is not clear whether magnetic diffusion or braking is more rapid. Despite the Hopper-Disney hypothesis, the general lack of observed rotation of expected magnitude might suggest that magnetic braking has been effective for many dark clouds, and therefore that magnetic fields are present which could in principle stabilize against gravitational collapse. In giant molecular clouds, the picture is equally unclear; condensations in M17 are not rotating (Elmegreen et al. 1978) while the Mon R2 cloud appears to rotate at $\sim$2 km s^{-1} pc^{-1} (Kutner and Tucker 1975). Magnetic fields seem possibly to be effective in some, but not all massive clouds.

The influence that an internal magnetic field has on cloud evolution is by no means clear. Mouschovias (1976a,b) finds in a 3-dimensional numerical analysis of low-density (diffuse) clouds that quasi-static solutions can be found, corresponding to slow collapse, and to only modest flattening of the cloud. Dissipation (CO cooling, turbulence) is not included; its effect would be to encourage faster collapse. In an effectively 1-dimensional study of the MHD equations of motion for a gas of ions and neutrals, which does not include dissipation effects, Langer (1978) finds that, for relevant densities and field sizes, only rather small-mass clouds have their collapse times significantly increased over the Jeans ($\sim$ free-fall) time. In Table 2, we compare Jeans time and actual collapse time from Langer's work, for our typical morphological types as listed in Table 1. We conclude that, with the exception of diffuse clouds and probably globules, the expected magnetic field strength doesn't slow the collapse rate significantly over the Jean's time. If dissipative mechanisms or any density gradients are included, the effect of the field would be decreased even further. For the relevant ranges of mass and density, these conclusions do not depend significantly on the magnetic field strength (in the range 1(-4) to 1(-3) gauss). Collapse times do depend strongly on the fractional ionization; unless this is considerably greater than believed, magnetic fields do not seem able to explain why molecular clouds do not collapse at roughly the free-fall rate.

Table 2. Collapse Time in the Presence of Magnetic Fields

Type	Jeans Time (yr)	Collapse Time (yr)		Assumed Ionization Fraction
		B = 1(-4)	B = 1(-3)	
diffuse clouds*	4(6)	> 1(9)		1(-4)
isolated dark clouds	6(5)	1.5(6) to 2(6)	1.5(6) to 2(6)	1(-8) to 1(-7)
large globules	2(5)	∿4(6)	∿4(6)	1(-7)
dark clouds with AB stars†	6(5)	7(5) to 1(6)	7(5) to 1(6)	1(-8) to 1(-7)
mol. clouds with O stars†	6(5)	7(5) to 1(6)	7(5) to 1(6)	1(-8) to 1(-7)
molecular cores	1(5)	1(5) to 2(5)	1(5) to 3(5)	1(-8) to 1(-7)

* B = 1(-5) gauss

† overall density n = 1(3) cm^{-3}

B. Comments on Fragmentation and Star Formation

The salient observational facts seem to be these:

i) only low mass stars (e.g., T Tauri) have formed in the lower mass isolated dark clouds.

ii) early-type stars (A,B,O) form only in clouds whose masses exceed ∿1(3) $M_\odot$. Such masses are a necessary but not sufficient condition for the presence of O stars. There is no clear distinction in the mass distribution of clouds that form O stars, and those that form only B or later stars.

iii) O stars (and possibly early B stars) appear preferentially near the edges of clouds (cf. e.g., Lada 1978).

Myers (1977) surveyed in the continuum molecular clouds that do not show obvious presence of O stars. Although deeply embedded stars as early as B1 were found, no O stars were detected. This result suggests that O stars appear at cloud edges because they tend to form there. Conversely, lower-mass stars form anywhere in a cloud.

Elmegreen and Lada (1977) and Elmegreen (1977) have explained iii) in terms of "stimulated" collapse--a sudden compression of a cloud's outer layers by a shock front associated with the spiral density wave, a nearby expanding HII region or supernova, or (on occasion) a cloud-cloud collision. These processes do not discriminate against formation of less massive stars, and in fact it is theoretically unclear whether massive stars are even favored. (In particular, Elmegreen (1977) has shown that the maximum fragment mass that will collapse under a shock depends on the 4th power of the time scale of the shock; HII region shocks have time scales ∿10 times those of supernovae). Two interesting questions arise from this picture. 1) Perhaps the massive stars formed earlier near the cloud edge, and the shock merely swept away obscuring material. 2) If shocks induce O-star formation in massive clouds, why not in low-mass clouds? A possible answer to 1) is that OB associations are apparently seen lying along a single line of increasing age away from the cloud. If this is really the case, it does suggest that successive formation of OB clusters was triggered by the previous cluster via HII shocks. A possible answer to 2) lies in a calculation of Jura (1976) which shows that clouds less massive than $\sim 10^3$ $M_\odot$ will not collapse under external pressures $p/k \sim 1500$ cm^{-3} K typical of spiral density waves, while values of $p/k \sim 10^5$ cm^{-3} K near supernovae and HII regions will induce collapse of clouds with $M \gtrsim 10$ $M_\odot$. Thus low-mass, isolated dark clouds do not suffer induced collapse because the spiral density wave is too weak, and because they never encounter HII regions or supernovae. Massive clouds, conversely, are susceptible to stimulated collapse by all of these means. We note that the threshold mass, $\sim 10^3$ $M_\odot$, for induced collapse by the spiral density wave, is observationally about the mass above which OB star formation occurs. This is a possible explanation of observational point ii).

To explain point i) we note that gravitational instability can certainly occur anywhere, anytime, inside a cloud as a result of local loss of internal energy by enhanced molecular cooling, magnetic diffusion, or turbulent viscosity. In the presence of a magnetic field and for sufficiently small ionization fraction ($X_i \lesssim 10^{-7} - 10^{-8}$), Langer (1978) finds that for a given density all fragment sizes have the same (i.e., Jeans) collapse time. In this case, multiple fragmentation appears possible, smaller fragments continuing to separate from larger ones. Suppression of massive stars may result. However, for larger X_i, smaller fragments collapse much more slowly than massive ones. In this case, multiple fragmentation is inhibited, and more massive stars tend to be produced. In isolated dark clouds, $X_i < 10^{-7}$ is indicated by observations, thus explaining lack of massive stars. In more massive clouds, the presence of massive stars (triggered by shocks) heats the surrounding gas, increases the ionization fraction, and therefore possibly inhibits formation of smaller stars.

Returning to point iii), alternative explanations to shock-induced formation of massive stars have been suggested. The critical mass for gravitational instability, with or without a magnetic field, can be written in terms of mass density ρ as $M_{cr} \propto \rho^{-\alpha}$. When coupled with a cloud of non-uniform density given by $\rho \propto r^{-\beta}$, the result is that massive stars tend to form preferentially in the outer regions (for α, $\beta > 0$ as expected in most cases). This suggestion, due to Silk (1978), does not appear to explain the lack of O stars in low-mass clouds.

Another long-standing hypothesis (cf. Mezger 1977) is that low-mass stars form first in a cloud; massive stars later. If so, then the more massive clouds, containing O stars, are older than the low-mass clouds (they could have become more massive by accretion, for example). This idea may be contradicted by recent work by Wootten et al. (1978) who believe that cold, lower-mass clouds have distinctly different chemical composition (in particular, proportionately more CO) than warmer, more massive clouds. Based on our present understanding of cloud chemistry, this result, if confirmed, would imply that the CO is closer to achieving equilibrium abundance in the cold, low mass clouds, which would therefore be the more evolved.

One might argue that in low-mass clouds O stars are simply not expected on the basis of the Salpeter mass function and the relatively few stars of all other types present. This argument is quantitatively untenable. We might also note that Larson's (1978) simulated calculations (no magnetic field) indicate that the largest fragments in a fragmenting cloud should have masses independent of the total mass of the cloud. The number of fragments is roughly the total cloud mass divided by the Jeans mass ($\sim$6 for large globules, $\sim$20 for isolated dark clouds, $\gtrsim$2000 for large molecular clouds).

V. MOLECULAR CLOUDS AND THE LARGE-SCALE CHARACTERISTICS OF THE GALAXY

Based on a galactic plane survey of CO, Gordon and Burton (1976) estimated the total mass of galactic H_2 at 2(9) $M_\odot$, somewhat greater than that found in giant clouds (4000 clouds x 3(5) $M_\odot$ per cloud = 1.2(9) $M_\odot$), but comparable to the total mass in HI (2.3(9) $M_\odot$). While the mass of the molecular component is only $\sim$5% of the mass of the galactic disk, giant molecular clouds are individually the most massive objects in the disk.

Stark and Blitz (1978) have discussed two important interactions that occur between molecular clouds and the galaxy as a whole. The first is the effect on large molecular clouds of tidal forces arising from the differential rotation of the disk. Assuming that the clouds are gravitationally bound, a typical giant cloud of radius 50 pc must have a mass in excess of 2(5) $M_\odot$, when at a typical galactocentric radius R of 6 kpc. The larger value of the tidal acceleration for $R < 4$ kpc could account for the absence of molecular clouds here (clouds in this region would have to be more massive or more compact than clouds at larger R). Alternatively, if the mass spectrum of clouds is everywhere the same, then masses $\geq$ 3(5) $M_\odot$ are implied. Note that some giant clouds are larger than 50 pc, implying even larger possible masses. (If gravitationally bound, Sgr B2 has a mass of $\gtrsim$5(7) $M_\odot$).

If even a small fraction of the total disk mass is concentrated in objects much more massive than stars, the dynamical relaxation time of the disk stellar system can be significantly reduced. Spitzer and Schwarzschild (1953) suggested that the observed increase in stellar velocity dispersions toward later main-sequence spectral types could be explained by a partial relaxation of the disk population, brought about by large-scale inhomogeneites in the interstellar medium. Stark and Blitz (1978) find that the relaxation time in the presence of the giant molecular clouds is $t_R \approx 7(8)$ yrs. Stars (O,B,A) with main sequence lifetimes $t_\ell << t_R$ do not relax from their initial velocity dispersion of $\sim$10 km s^{-1}, whereas late-type stars with $t_\ell > t_R$ relax toward higher dispersions. The predicted values of velocity dispersion as a function of t_ℓ/t_R are quantitatively in agreement with observations. This implies that there cannot be many giant clouds with $M > 3(5)$ $M_\odot$, or the velocity distribution of disk stars would be more relaxed than is observed.

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