The Formation of Molecular Clouds

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ABSTRACT

In a recent paper, Elmegreen (2000) has made a cogent case, from an observational point of view, that the lifetimes of molecular clouds are comparable to their dynamical timescales. If so, this has important implications for the mechanisms by which molecular clouds form. In particular we consider the hypothesis that molecular clouds may form not by in situ cooling of atomic gas, but rather by the agglomeration of the dense phase of the interstellar medium (ISM), much, if not most, of which is already in molecular form.

Key words: galaxies:ISM – ISM:clouds – ISM:molecules – stars:formation

1 INTRODUCTION

Recent advances in our theoretical and observational understanding are combining to imply that the lifetimes of molecular clouds are much less than they had been previously supposed. Indeed it seems, as discussed in Section 2 below, that molecular clouds form, produce stars and disperse all within few dynamical timescales. These conclusions have strong implications about the way in which molecular clouds can form, and we argue below (Section 3) that the gas out of which they are formed is already predominantly molecular.

This, in turn, has implications for the nature of the ISM in the disks of spiral galaxies which we discuss in Section 2. We discuss and summarise our conclusions in Section 3.

2 THE LIFETIMES OF MOLECULAR CLOUDS

The properties of Giant Molecular Clouds (GMCs) have been reviewed by Blitz (1991, 1994), and by Williams, Blitz & McKee (2000). GMCs appear to be discrete objects, with well defined boundaries, and are the sites of essentially all the star formation that is occurring in the Galaxy. The size distribution of clouds means that most of the mass of clouds (and hence most of the star formation) is in the most massive clouds. With this in mind, we shall for our present purposes take a typical GMC to have a mass $M_{cl} \sim 5 \times 10^4 M_{\odot}$, and radius $R_{cl} \sim 30$ pc (Solomon et al., 1987; Leisawitz, 1990; Blitz, 1994). Such a cloud has a mean baryon number density of $n \sim 200$ cm$^{-3}$, corresponding to a molecular hydrogen number density of $n(H_2) \sim 80$ cm$^{-3}$, and has a dynamical timescale of $t_{cl} \sim (R_{cl}^3 / GM_{cl})^{1/2} \sim 4 \times 10^8$ y.

It has long been argued (Zuckerman & Evans, 1974; Zuckerman & Palmer 1974) on global grounds that the lifetime of the molecular gas, which is visible in the form of molecular clouds, must exceed the dynamical timescales of the clouds by about an order of magnitude. This is because if one takes the total mass of $H_2$ observed in the Galaxy, $M(H_2) \sim 2 \times 10^7 M_{\odot}$ and divides by the dynamical timescale $t_{cl}$ one obtains an estimated star formation rate of $\sim 500 M_{\odot}$/y. This exceeds the currently observed rate by a factor of about $\sim 100$ (Scalo, 1986; Evans, 1999). Thus the molecular gas in the galaxy is being converted to stars on a timescale which exceeds its dynamical timescale by a factor of $\sim 100$. It is important to realise that since stars form only out of this molecular gas, this statement remains true independent of whatever else might be going on. This argument on its own, in fact, tells us nothing directly about the lifetimes of molecular clouds, but there is a connection through the concept of the efficiency of star formation.

For example, if all the visible molecular gas turns into stars, and none of it is dispersed back to atomic gas, then the efficiency of star formation is 100 per cent, and each molecular cloud must have a lifetime of $\sim t_{cl}$. However, estimates of the dispersal timescale for molecular clouds (Bash, Green & Peters, 1977; Blitz & Shu, 1980; Leisewitz, Bash & Thaddeus, 1989; Blitz, 1994) suggest that the average age or lifetime of a typical GMC is around $3 \times 10^7$ y, or around $10 t_{cl}$. If so, then the efficiency of star formation (as de-
fined here) for a typical molecular cloud is around \( \sim 10 \) per cent.

It was quickly realised that the picture of molecular clouds lasting for around \( \sim 10 \) years is problematic, because the internal motions within the clouds are observed to be highly supersonic. GMCs obey a size-linewidth relation which indicates internal velocity dispersions of around \( \sigma_{\text{cl}} \sim 3-5 \) km s\(^{-1}\) (Blitz 1994). This exceeds the thermal (sound) speed \( (c_s \sim 0.2 \) km s\(^{-1}\)) in the cool (\( T_{\text{th}} \sim 10 \) K) molecular gas by an order of magnitude. In the absence of any mechanism to prevent it, such supersonic turbulence would die out on the crossing timescale of the cloud, \( t_{\text{cl}} \sim R_{\text{cl}}/\sigma_{\text{cl}} \sim 7 \times 10^6 \) yr. In the standard scenario molecular clouds are envisaged as being supported by (turbulent) magnetic fields (Arons & Max 1975; Lizano & Shu 1989; Carlb erg & Pudritz 1990; Bertoldi & McKee, 1992; Allen & Shu, 2000), and star formation within the clouds is envisaged as being controlled by the rate at which material can escape from the field lines by the process of ambipolar diffusion (Mestel, 1965; Mouschovias, 1991).

However, a succession of numerical simulations (Mac Low et al., 1998; Padoan & Nordlund, 1999; Ostriker, Gammie & Stone, 1999; Heitsch, Mac Low & Klessen, 2001; see the review by Vázquez-Semadeni et al., 2000) on the dissipation of supersonic turbulence in non-magnetic, slightly magnetic, and highly magnetic media have demonstrated convincingly that the dissipation timescale is approximately the same in each case and is of order the crossing timescale, \( t_{\text{cl}} \). In hindsight (Goldreich & Kwan, 1974; Field, 1978) this is not too surprising because the hoped for effect of the magnetic fields in cushioning the shocks and so preventing dissipation can only work if the motion is exactly at right angles to the field lines. In a general turbulent medium the field lines and velocities are not usually orthogonal and so the fluid moves freely along the field lines and shocks almost as readily as in a non-magnetic medium.

In addition, it is no longer clear that ambipolar diffusion is the dominant mechanism for regulating star formation. This is mainly because the ambipolar diffusion timescale is apparently too long (Myers & Kersonsky 1995; Nakano, 1998; Caselli et al., 1998; Ward-Thompson et al., 1999; Burkert & Lin 2000; but see Ciolek & Basu, 2001). Moreover, the original picture of the formation of a magnetically supported self-gravitating core, followed by slow removal of the magnetic support, gives rise, in general, to a centrally condensed hydrostatic configuration, which leads to the formation of a single star (Boss, 1987; Myhill & Kaula, 1992). Most stars are formed as members of binary and multiple stellar systems, and to obtain such multiple fragmentation it may be necessary for the collapse event to be instigated dynamically, and for the collapsing material to be already free of magnetic support (Pringle, 1989; see the review by Pringle, 1991). The basic problem here can be expressed simply in terms of the following question: why does the self-gravitating core of a molecular cloud form \( \sim 1000 \) stars each of mass \( \sim 1 \) solar mass, rather than forming a single star of mass \( \sim 1000 \) solar mass? The considerations here are analogous to those relevant to the formation of globular clusters (Murray & Lin, 1989, 1992). There may still be a problem with the removal of magnetic support because molecular clouds are observed to contain magnetic fields (see, for example, Williams et al. 2000) with strengths such that the magnetic energy density is comparable to the turbulent kinetic energy (as might be expected for an equipartition field in a turbulent medium). Some consideration has been given to the removal of magnetic support, at least for a sufficient fraction of the gas to account for the observed star formation efficiency, by magnetic reconnection (Clifford & Elmegreen, 1983; Norman & Heyvaerts, 1985; Shu, 1987; Lubow & Pringle, 1996; Norman et al., 1996).

There is also a major problem from an observational point of view in that the simple initial concept that star formation continues at a steady rate throughout the lifetime of a GMC (whether or not this rate is governed by ambipolar diffusion) is no longer sustainable. Because all molecular clouds contain substantial amounts of star formation, it is already clear that the onset time \( t_{\text{onset}} \) (that is, the time from the formation of a GMC to the onset of star formation) must be much less than the lifetime of a cloud and is at most of the order of a crossing timescale (Beichman et al. 1986; Jessup & Ward-Thompson, 2000; Myers, 1999). Elmegreen (2000) has taken this argument a stage further and makes a strong case that the star formation in a GMC occurs within one or two crossing times of its formation. If so, this implies that the mean efficiency of star formation (as defined here), averaged over all molecular gas, can only be a few per cent. His arguments are based on the estimates of cluster ages relative to the dynamical times and on the hierarchical structure of embedded young clusters. Moreover, comparisons of the ages of young clusters and their association with molecular gas both in the Galaxy (Leisawitz, Bash \& Thaddeus, 1989) and in the LMC (Fukui et al 1999) indicate that the dispersal of a cloud in which star formation has occurred only takes a timescale of 5-10 Myr, i.e. one or two dynamical timescales. This view is reinforced by the work of Ballesteros-Paredes, Hartmann \& Vázquez-Semadení (1999) who argue that in the Taurus-Auriga complex the lack of post T Tauri stars (ages \( > 5 \) Myr) compared to the T Tauri stars (ages \( \sim 1 \) Myr) indicates that the molecular clouds come together, form stars and disperse all within a few Myr.

3 FORMATION MECHANISMS

If we accept the conclusions outlined in the previous section that molecular clouds form, produce stars and disperse all within a few dynamical timescales, then this sets severe constraints on how molecular clouds can form. This in turn has serious implications for the initial conditions of the star formation process itself, and thus for the star formation rate and, perhaps, for the IMF (Elmegreen 2000). The formation of a molecular cloud on a timescale roughly equal to its own dynamical timescale can be achieved in two obvious ways, which we discuss below.

\[ \dagger \] Note that \( t_{\text{cl}} \) and \( t_{\text{onset}} \) are different physical quantities. One is dynamical and the other kinematic. The general observation that for most clouds \( t_{\text{onset}} \sim t_{\text{cl}} \) would imply that most clouds are in approximate virial equilibrium, were it not for the fact that cloud masses are often inferred using the (implicit) assumption of virial equilibrium.
3.1 Formation from atomic gas, HI

The standard picture for the formation of molecular clouds follows from the assumption that the only molecular gas in the Galaxy is the gas which can be readily observed (for example in CO surveys, Solomon et al., 1987). In this picture molecular clouds are formed in situ from atomic gas. If the gas out of which the molecular cloud is formed is initially HI, then it is necessary for HI gas to collide in such a way that a sufficient amount of H$_2$ is formed sufficiently quickly and in a sufficiently small volume.

Our typical molecular cloud has a mean baryon number density of $\rho \sim 200$ cm$^{-3}$ and a virial temperature of $T_{\text{vir}} \sim 10^3$ K$^\dagger$. As long as the postshock gas has a pressure as high as this, then the formation of molecular gas from atomic gas on a short enough timescale (of order a few times $10^2$ y) appears to be achievable (Vázquez-Semadeni et al., 1996; Ballesteros-Paredes et al., 1999; Koyama & Inutsuka, 2000).

Let us consider the nature of the HI gas out of which such a cloud might have formed. The mass-radius relation for molecular clouds implies approximately that they all have the same baryon surface number density of $N_H \sim 2 \times 10^{22}$ cm$^{-2}$. If this amount of material has to be assembled in a time $t_{\text{cl}} \sim 4 \times 10^5$ y from material moving at a pre-shock velocity of $V_0$ and with a pre-shock density $n_0$, then we find that $n_0 \sim N_H/V_0t_{\text{cl}} \sim \bar{n}\sigma_{\text{cl}}/V_0$, that is

$$n_0 \sim 10^2(V_0/10\text{ km s}^{-1})^{-1}\text{cm}^{-3}, \quad (1)$$

where we have assumed that the HI gas is moving at a velocity of $V_0$ corresponding either to the shock velocity in a spiral shock, or to the observed galactic dispersion velocity of around 5-10 km s$^{-1}$ (Dickey & Lockman, 1990). If this gas had been in pressure equilibrium with the ISM, it would have had to have a temperature of $\sim 100$ K. That is, it was already cool enough to have been molecular. Moreover, since the pre-shock velocity, $V_0 \sim 10$ km s$^{-1}$, is only a factor of two or three greater than the internal velocity dispersion of the resultant GMC, $\sigma_{\text{cl}} \sim 3 - 5$ km s$^{-1}$, then for the GMC to be assembled in a crossing time requires that the column density of the preshock gas, parallel to the shock, must be not less than two or three times smaller than the resulting column density of the GMC, i.e. $N_H \gtrsim 10^{22}$ cm$^{-2}$. This amount of column density is enough to provide self-shielding against ambient UV radiation.

Thus, the formation of molecular clouds directly from atomic gas requires, as a prerequisite, the existence of atomic gas which is already dense ($n_0 \sim 10^5$ cm$^{-3}$) and cool ($T_{\text{th}} \sim 100$ K) enough to be mainly molecular. In addition, we note that the Jeans length in such gas is $R_J \sim 3$ pc, and the corresponding Jeans mass is $M_J \sim 8000 M_\odot$. These quantities are already much less than the masses and scale-sizes required for the pre-shock gas if it is to form a GMC with $M_{\text{cl}} \sim 5 \times 10^5 M_\odot$ and $R_{\text{cl}} \sim 30$ pc, and imply that self-gravity was already playing a significant role in the pre-shock gas. We conclude that it is not evident that the standard picture of forming molecular clouds directly from atomic gas is one which is internally self-consistent.

3.2 Formation from molecular gas, H$_2$

If the gas from which GMCs form is already molecular, then the above problem is replaced by the conundrum that almost all the observed molecular gas in the Galaxy is in molecular clouds and is already involved in the process of forming stars. Thus we would have to argue that not only is a substantial fraction of the mass in the ISM (say, as much as a half) in molecular form, but that it has yet to be detected. Before dismissing this out of hand, it seems fruitful to explore such a possibility.

Allen and coworkers (Allen, 1996; Allen et al., 1986; Tilanus et al., 1998; Tilanus and Allen, 1989) have explored the details of shock structure and star formation in the spiral arms of two spiral galaxies M51 and M83. If, according to the standard scenario, molecular clouds form from atomic gas in shocks one would expect to see as one progresses through a spiral shock: first HI, then H$_2$, and then star formation. In contrast, what they find is that one sees first narrow dust lanes and enhanced radio continuum emission, indicative of the position of the shock, and then, downstream, HI, HII and young stars. They argue that what happens at the spiral shock is that molecular gas already present is collected together into denser agglomerations where it forms stars. Downstream of the shock, the young stars dissociate the molecular gas to form HI, and then ionize the atomic gas to form HII.

In this picture one might envisage the interarm ISM to consist of (say) 50/50 molecular/atomic gas by mass, although almost all HI by volume. The H$_2$/CO would be in dense wisps (not in blobs or droplets as it is not self-gravitating and has no cohesiveness). But in a shock, such as a spiral arm, the molecular gas (having a non-negligible fraction of the mass and momentum) can come together (c.f. Shu et al., 1972; Lubow, Balbus & Cowie, 1986). In the interarm gas, the molecular gas must be cold (say $T \sim 5$ K) so that it is not readily detectable, and it becomes visible only where it is heated sufficiently to radiate (say $T \gtrsim 10$ K). Thus molecular clouds represent the regions in the ISM where the molecular gas becomes detectable. The reason the gas becomes detectable is that it is heated by the new-born stars. Thus, in this picture, it is no surprise that $t_{\text{cool}}$ is so short.

The detectability of the CO(1-0) millimetre line emission from the heated surfaces of spherical model GMCs excited by an ambient UV flux, and the relationship between the CO emission to the amount of $H_2$ present, have been calculated in detail by Kaufman et al. (1999). Their models describe many aspects of the far-infrared and millimetre/sub-millimetre line and continuum emission from photo-dissociation regions (PDRs) over a wide range of parameter space. Among many important results, such as the use of line ratios as diagnostics for physical conditions on the surfaces of molecular clouds, these authors discuss the conditions under which one can use the CO(1-0) luminosity from the cloud surface to estimate the mass of $H_2$ within

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$\dagger$ The fact that the virial pressure $p(H_2)T_{\text{vir}} \sim 10^5$ K cm$^{-3}$ exceeds the ambient pressure ($\sim 10^4$ K cm$^{-3}$; Dickey & Lockman, 1990) in the interstellar medium by one or two orders of magnitude had been part of the traditional argument that molecular clouds must be self-gravitating objects (independent of the estimates of the actual mass which depends on estimates of the CO/H$_2$ ratio). If the clouds only last a time of order their crossing timescales, however, this virially based argument is no longer valid.
the cloud. From their results (Figure 19 in Kaufman et al., 1999), it is evident that the standard ratio relating CO(1-0) luminosity to \( H_2 \) mass, which is widely used by many millimetre observers (the "X-factor"), applies only over a limited range of parameter space. In particular it applies to gas with solar metallicity, in high density clouds (\( n \sim 10^4 \text{ cm}^{-3} \)), subject to bright UV fluxes (\( \sim 1-100 \) times the value in the ISM near the sun) and with total cloud column densities such that \( N_H \gtrsim 10^{22} \text{ cm}^{-2} \). At lower volume densities, the X-factor considerably underestimates the amount of \( H_2 \) present. In particular, for the standard GMC with \( n \sim 200 \text{ cm}^{-3} \) and \( R \sim 30 \text{ pc} \) (and thus with \( N_H \sim 2 \times 10^{21} \text{ cm}^{-2} \)) subject to the local ISM value of the UV flux (\( G_0 \sim 1 \)) and for solar metallicity (\( Z \sim 1 \)), the use of the assumed standard X-factor to convert the observed CO(1-0) millimetre flux to \( H_2 \) mass underestimates that mass by almost an order of magnitude. This discrepancy get worse for larger UV fluxes, since at these baryon densities the CO brightness is essentially independent of UV flux, and the CO is more readily dissociated than the \( H_2 \).

In fact, taken at face value, the results of Kaufman et al. (1999) indicate that the CO(1-0) emission observed at relatively low angular resolution in the disks of nearby galaxies is not likely to be produced in PDRs. It may be that a more likely source of the excitation is low-energy cosmic rays (Suchkov et al., 1993). This would explain more simply why galaxies such as M83, which are bright in the non-thermal radio continuum, are also correspondingly bright in CO(1-0) emission (Adler et al., 1991; Allen, 1992). This would also account for the high CO brightness in the arms of M51, where the non-thermal radio emission is also bright, and the relative absence of CO emission between the arms, where the radio continuum surface brightness is correspondingly lower. In this picture, the actual relationship between CO(1-0) luminosity and the amount of \( H_2 \) in a galaxy depends sensitively on the local cosmic ray density (Suchkov et al., 1993) and cannot be readily determined without information about that component of the ISM.

4 IMPLICATIONS FOR THE NATURE OF THE ISM

Might this idea that a substantial fraction of the ISM is in the form of molecular gas be a generic picture for the ISM in spiral galaxies? It has usually been thought that the fraction of ISM in atomic form increases along the Hubble Sequence towards the late-type galaxies (see the review by Roberts & Haynes 1994), and that the atomic fraction dominates the molecular by an order of magnitude or more for a significant number of star forming galaxies of types Sc and later (Young & Knezek 1989). However, Smith et al. (2000) find that in the giant Scd spiral M101 the molecular gas is found with a narrow range in density from 30-1000 cm\(^{-3}\) near star forming regions at all radii in the disk out to a distance of at least 26 kpc. They conclude that most of the ISM throughout the disk of this galaxy is in molecular form.

A frequent objection to the concept that most of the ISM is in molecular form (apart from astronomers’ healthy scepticism about the existence of something that is hard to observe), is that molecular gas is quickly dissociated back to atomic form by the general UV background photon flux. The relevant photons are in the range 6.5 – 13.6 eV for \( H_2 \) and 11.1 – 13.6 eV for CO. In this wavelength range the background photon flux is approximately \( U_{\lambda} \sim 4 \times 10^{-17} \text{ erg s}^{-1} \text{ A}^{-1} \) (Habing, 1968; Greenberg, 1971; Lang, 1978; Gondhalekar et al., 1980; Redfield & Linsky, 2000). This gives a photo-dissociation timescale for an isolated CO or \( H_2 \) molecule of around 100 – 300 y. We should bear in mind, however, that the UV flux corresponds to the UV flux measured in the vicinity of the Sun, and that this may be an overestimate of the UV photon flux seen at a general point in the disk of the Galaxy, if, for example, the Sun is in a low density bubble in the ISM (Cowie & Songalia, 1986; Lallement & Bertin 1992; Lallement et al., 1995). In addition, molecular gas can exist if it is sufficiently shielded. The shielding is provided by dust, present in both the atomic and the molecular components of the ISM, and a column density of 21 \( K_n \sim 10^{43} \text{ cm}^{-2} \), which corresponds to a visual extinction of \( A_V \sim 0.5 \), is generally taken to be what is required. Thus, we should ask: what is the mean extinction experienced at a typical point in the disk of the Galaxy? This is not an easy question to answer for our own Galaxy, and we need to look for evidence in external systems. Here, there is growing evidence that the discs of galaxies are not as transparent as has been usually been assumed. For example, White et al. (1996), Berlind et al (1997) and Gonzalez et al (1998) find that disk galaxies contain a lot of patchy dust, with average extinctions through the disk, even in the interarm regions, being around \( A_V \sim 0.5 \). Comparable, but somewhat lower values are found by Domingue, Keel & White (2000), and by White and Keel (2001). These extinctions are along lines of sight more or less perpendicular to the gas disk plane, and so presumably pass through at most around a few hundred parsec of the galaxy’s ISM. This implies that for lines of sight within and along the disk plane, relevant to the light paths from hot stars to molecular gas, the extinctions would be correspondingly higher. Thus, presumably in the patches, and perhaps in between, molecular gas would be able to exist without being subject to UV photo-dissociation.

How do we expect the molecular gas to be distributed? We have already argued that most of it cannot be in large enough agglomerations to be self-gravitating – otherwise it would be forming stars (Note that there may be some low level agglomeration of such material corresponding the interarm star formation). In between spiral shocks, the gas (atomic and molecular) is moving supersonically on essentially particle orbits. There is not time between spiral arm shocks for hydrostatic equilibrium to be established perpendicular to the plane of the disk (the timescale to achieve this is approximately the same as the orbital timescale around the centre of the galaxy). Thus, as long as the energy input from star-formation at each shock provides sufficient velocity dispersion, there is no dynamical reason why the molecular gas should be distributed very differently from the atomic component. Koyama & Inutsuka (2000) in their computations of the formation of molecular gas in shock-compressed layers argue that the instabilities in the thermally collapsed post-shock layers break up the molecular gas into tiny molecular cloudlets. The idea that dense gas may reside in the form of unresolved clumps is not new (see, for example, the review by Evans, 1999), and the concept is given further credence by observations of high galactic latitude translucent clouds (the Galactic “cirrus” clouds).
These are parcels of dense gas which are found at heights of around 100 pc out of the galactic plane. Despite being subject to the full force of the interstellar UV radiation field, they contain molecular gas with a surface density of \( N(H_2) \sim N(HI) \gtrsim 4 \times 10^{20} \, \text{cm}^{-2} \) (Reach et al., 1994). More recent investigation of the radiation properties of these clouds, in particular the ratios of emission in various transitions of CO, suggests that the bulk of the molecular gas may be in high density \( (n \gtrsim 10^4 \, \text{cm}^{-3}) \), low temperature \( (T \sim 8 \, \text{K}) \) cells of size around \( \sim 0.01 \text{pc} \) (Ingalls et al., 2000).

5 CONCLUSIONS

We have considered the implications of the argument advanced by Elmegreen (2000) that the lifetimes of molecular clouds are comparable to their dynamical lifetimes (or to their crossing times), and have advanced the argument that this might have interesting implications as to the the nature of the interstellar medium. In particular, we have considered the hypothesis that a large fraction (perhaps about a half) of the the interstellar medium is in the form of molecular gas, which is too cool to be detected. If this hypothesis is correct, then this changes our picture of the nature of molecular clouds in a fundamental way.

In this scenario, molecular clouds are, like the tips of icebergs, just the small but visible component of a much larger mass of molecular gas. That is, the things we call molecular clouds are in reality only parts of larger structures of molecular gas, and are simply those parts which are illuminated by nearby heating sources (new-born stars). This cool gas is spread throughout the atomic component of the interstellar medium and is not in general self-gravitating. It is compressed in spiral shocks, and in these shocks a sufficient fraction of it becomes self-gravitating enough to initiate star formation (c.f. Shu et al., 1972; Lubow et al., 1986).

This in turn implies, first, that the initial conditions for the onset of star formation are likely to be dynamic, rather than quasi-static, and, second, because the gas has already been cool and dense for some time, that it can already be sufficiently free of magnetic fields to undergo immediate and unimpeded gravitational collapse. This provides conditions favourable to the formation of binary and multiple stars (Pringle, 1989).

Because the clouds of visible (heated) molecular gas exist only for a few of their dynamical or crossing timescales – either because the they have been dispersed by the effects of star formation, or because the strong initial burst of UV radiation from new-born massive stars has died away, which also occurs on a timescale of \( \sim 10^7 \, \text{y} \) – there is no need for them to be in virial equilibrium. Indeed the shapes of molecular clouds are usually indicative of non-relaxed dynamical structures. This implies that the assumption of virial equilibrium should not be used in estimating the masses of molecular clouds.

Furthermore, the usual interpretation of the size-linewidth relations in terms of virial equilibrium are also likely to be invalid, as are estimates of the masses of molecular clouds based on the usual assumption of virial equilibrium. Indeed the aggregate properties of molecular clouds, such as the size-linewidth relation, are somewhat different to what one might observe for a selection of random positions embedded in a turbulent gas (Miesch, Scalo & Bally, 1999; Ballesteros-Paredes, Vázquez-Semadeni & Scalo, 1999; Scalo, 1990), although it is not obvious to what extent the ISM should be expected to display fully developed turbulence, rather than just a randomly disordered velocity field.

In summary, if the hypothesis considered in this paper is correct, then it provides (at least partial) explanation for the following:

- The star formation in a molecular cloud occurs within one or two crossing times of its formation.
- The lifetimes of molecular clouds are short, and comparable to a few crossing times.
- Molecular clouds do not appear to be in dynamical equilibrium.
- The onset time for star formation is shorter than the ambipolar diffusion timescale.
- Most stars form in clusters and are binary (or multiple) rather than single.

It is evident, however, that the validity of the somewhat speculative ideas put forward in this paper requires testing through further work, both observational and theoretical. On the theoretical side, the most obvious lacuna is in understanding the physical properties, and the dynamics, of the hypothesized cold phase of what is evidently a multi-phase interstellar medium, especially its behaviour in galactic shocks. Current hydrodynamic and magnetohydrodynamic codes should be capable of tackling this problem (c.f. Wada & Norman, 1999, 2000). On the observational front, the most pressing need is to find some means by which limits can be set to the quantity of hitherto unobserved molecular gas within the disks of our own and of other galaxies. An initial attempt to provide limits to the amount of cold dust in our galaxy are given by Reach et al. (1995) and by Lagache et al. (1998), and a more general discussion is given by Combes & Pfenniger (1997).

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