Abstract. Molecular clouds (MC) are the densest and coldest component of the interstellar gas, and the sites of star formation. They are also turbulent and fractal and their masses and sizes span several orders of magnitude. It is also generally believed that they are close to Virial equilibrium (VE). Since this statement has been questioned by a number of authors, with important implications on molecular clouds’ lifetimes, we will review this subject within the context of a turbulent ISM. In this framework, there is significant numerical evidence that MCs are not in VE, that there is a strong exchange of mass, momentum and energy between clouds and their surrounding medium, and that it is difficult (if not impossible) to form quasistatic cores inside MCs, suggesting that they must be transient, short-lived phenomena. Thus, their formation and disruption must be primarily dynamical, and probably not due to just a single mechanism, but rather to the combination of several processes. This picture seems consistent with recent estimates of ages of stars in the solar neighborhood.

Keywords: ISM: clouds, turbulence ISM: kinematics and dynamics, stars: formation

1. Virial Theorem: Are Clouds Actually in Virial Equilibrium?

The Virial theorem can be derived from the momentum equation by dotting it by the position vector and integrating it over the volume of interest (see, e.g., Parker, 1979; Spitzer, 1982; Shu, 1989; Hartmann, 1998). Due to lack of space, we will not write down the equation and their terms. A clear and full description of either the Lagrangian and Eulerian versions can be found in MicKee and Zweibel (1992) (see also Ballesteros-Paredes and Vázquez-Semadeni, 1997; Ballesteros-Paredes et al., 1999a). Here we just mention that it involves the calculation of all the energies of the clouds, as well as the evaluation of pressures at the clouds’ surface, and time derivatives of the moment of inertia. In the Eulerian version, additional terms involving mass flux through the clouds’ surfaces appear.

It is frequently encountered in the literature that VE is applicable to MCs (e.g., McKee, 1999 and references therein). This statement is generally based on the theoretical assumption that all forces are in balance (Spitzer, 1982), or on the observational fact that clouds exhibit near equipartition between gravity and internal energies. Nevertheless, in a constantly stirred turbulent ISM (see chapter by MacLow, this volume), it is not clear that the forces will balance. Furthermore, equipartition between energies should not be considered evidence for VE. The only probe that VE admits is to measure the second time derivative of the moment of inertia, \( \ddot{I} \), and check that it is zero. Such a probe is not possible in an observational way. However, it has been measured in numerical simulations of modeled clouds.
by Ballesteros-Paredes and Vázquez-Semadeni (1997), who have shown that, for an ensemble of clouds in simulations of the ISM, the clouds are not in VE. They obey the Virial Theorem, but the second time derivative of the moment of inertia is not zero.

The VE assumption ($\ddot{I} = 0$) implies either that clouds are not redistributing their mass inside, or that the variation of their mass distribution is constant with time. Both statements seem highly implausible in a dynamical, nonlinear ISM. McKee (1999) has suggested two possibilities, in order to assume VE for MC: One is that, for a single cloud, $\langle \ddot{I} \rangle = 0$ if the considered averaging time is much larger than the dynamical timescale of the cloud, $t_{\text{avg}} \gg t_{\text{dyn}}$. The other is that for an ensemble of clouds, some of them may have positive values of $\ddot{I}$, and some others will have negative values, so that VE holds for the ensemble. Regarding the first assumption, there is a hypothesis behind it: the cloud has to be oscillating around a mean shape without a strong redistribution of mass. Nevertheless, in a nonlinear regime, any variable may change in an arbitrary way, and not necessarily the mean values will average to zero. Furthermore, recent numerical and observational evidence (cf. §2) suggests that the lifetimes of the clouds are not significantly larger than their own dynamical times (i.e., they are transient), and averaging over large timescales may be meaningless. Concerning the second assumption, the analysis by Ballesteros-Paredes and Vázquez-Semadeni (1997) shows that variations of the moment of inertia span up to 7 orders of magnitude (in absolute value) between the largest clouds and the smallest. Thus, it is not clear that an average for such large scatter will be representative of the actual dynamics of the clouds. Moreover, even if $I$ averages to zero for the cloud ensemble, this does not alter the fact that clouds are individually out of VE.

It is important to mention that, however, for clouds in numerical simulations, there is approximately an energy equipartition between gravitational, kinetic, magnetic and internal energies Ballesteros-Paredes and Vázquez-Semadeni (1995), in agreement with observational determinations (e.g., Myers and Goodman, 1988), suggesting that, in particular ‘Virial mass’ estimates (which would be better called ‘energy equipartition mass’) are of the same order of magnitude than the actual mass, in spite of VE probably not being applicable.

It is also widely believed that the turbulent kinetic energy provides support for clouds against their self-gravity (see, e.g., Chandrasekhar, 1951; Bonazzola et al., 1987, Vázquez-Semadeni and Gazol, 1995). However, this is only part of the turbulent motions, and only if they were confined to scales much smaller than the cloud sizes it could be the only effect (Chandrasekhar and Fermi, 1953; Leorat et al., 1990; Padoan, 1995; Ballesteros-Paredes et al., 1999a, Klessen et al., 2000). In reality, interstellar turbulence is a multiscale phenomenon, and there is observational and numerical evidence that turbulence at very different scales is present in MC, with most of the energy residing in the large-scale motions, as in most turbulent flows (Scalo, 1987; Norman and Ferrara, 1996; Falgarone et al., 1998; Ballesteros-Paredes et al., 1999a; Avila and Vázquez-Semadeni, 2001; Ossenkopf
and McLow, 2002; Brunt, 2002). Moreover, turbulence in MCs is highly compressible, and compressible turbulent modes have the effect of producing density enhancements at scales smaller than their own, thus promoting, rather than preventing, gravitational collapse. This process is usually referred to as ‘turbulent fragmentation’ (e.g., Padoan, 1995). Thus, turbulent modes at a given scale are most likely to have a dual role, providing support toward larger scales while simultaneously promoting collapse of smaller ones (Klessen et al., 2000). The precise outcome of collapse or support must be the result of the total energy involved in the compressible modes of turbulence at large scales against the energy involved in the smaller scale modes.

On the other hand, it is found that surface and volumetric terms in the Virial theorem are comparable in order of magnitude (Ballesteros-Paredes and Vázquez-Semadeni, 1997, see also Ballesteros-Paredes et al., 1999a), suggesting that clouds are actually interchanging mass, momentum and energy with the surrounding medium. This result is reasonable because the ISM is highly dynamic, with strong energy injection by stellar outflows, spiral density waves, HII region expansions, etc. In fact, thermal and kinetic pressure confinement has been criticized by Ballesteros-Paredes et al. (1999a), arguing that thermal pressure constancy is relatively meaningless in a medium in which the ram pressure is significantly larger than the thermal one, and that ram pressure ‘confinement’ is meaningless, because, when the motions are at the scales of the cloud itself, the cloud is actually a (transient) turbulent fluctuation, rather than a persisting entity that somehow requires to be ‘confined’. Recent observations confirming this picture are presented by Jenkins and Tripp (2001).

The preceding discussion questioning the assumption of VE for molecular clouds has an analogue at the level of their dense cores. Although in the standard models for star formation, low-mass protostellar cores are assumed to be in quasi-hydrostatic equilibrium (e.g., Mouschovias, 1991, Shu et al., 1987, and references therein), this view has begun to change recently, especially among the proponents of a turbulent scenario for molecular cloud structure and star formation (e.g., Scalo, 1987; Elmegreen, 1994; Padoan, 1995; Ballesteros-Paredes et al., 2000; Klessen et al., 2000; Padoan and Nordlund, 2002; Vázquez-Semadeni et al., 2002a, 2002b). For instance, Ballesteros-Paredes and Vázquez-Semadeni (1998) have presented preliminary results suggesting that the velocity structure of the so-called ‘coherent cores’ (dense molecular cores with a non-thermal velocity dispersion that becomes constant with size at small – below few × 0.1 pc – scales; Goodman et al., 1998), may be interpreted as the signature of the collision between gas streams. Similarly, Padoan et al. (2001), have found a velocity dispersion-column density relationship which appears in shocked generated cores in their simulations, as well in observed protostellar cores, suggesting that protostellar cores must be formed by supersonic turbulence.

Furthermore, a particular argument against the possibility that cores within MCs are in hydrostatic regime has been given by Vázquez-Semadeni et al. (2002, see
also Tohline et al., 1987; Taylor et al., 1996; Ballesteros-Paredes et al., 1999a, Vázquez-Semadeni et al., 2002b). Molecular clouds are nearly isothermal, and thus a typical Bonnor-Ebert (BE) configuration (Ebert, 1955; Bonnor, 1956), in which a tenuous, hotter medium provides confining pressure, cannot exist, because the core and its surrounding medium are at roughly the same temperature. Thus, cores must be extended, rather than truncated structures. Now, extended equilibrium isothermal structures can be shown to always be gravitationally unstable, and so, if a turbulent, dynamic compression brings the core near a hydrostatic configuration, the core will simply proceed to collapse if it reaches gravitational instability, or else will re-expand back to the average mean density of the cloud. However, cores that re-expand will be delayed by their own self-gravity, spending more time in this process than if they proceed to collapse. This result is consistent with the fact that MC typically contain more starless than star-forming cores (Taylor et al., Lee and Meyers, 1996, 1999; see also Evans, 1999 and references therein).

Of course, the above discussion does not apply if the dense cores are embedded in a hotter, more tenuous medium, which can then confine the core. B68 is probably the best example of a core in this situation (Alves et al., 2001; Hotzel et al., 2002a, 2002b), although there are some pieces of inconsistency: First, the cloud is not round, or oval in a regular way. This makes implausible that it can be in precise hydrostatic equilibrium. Second, their recently reported observations show motions of 0.25–0.5 the sound speed, suggesting that the cloud is near but not precisely in hydrostatic equilibrium. Third, the fitted Bonnor-Ebert profile by Alves et al. (2001) implies a temperature of 16 K, and, even at this temperature, marginal instability. The actual temperature is a factor of 30–50% lower (~ 10 K, see Hotzel et al. 2002a), and thus the thermal support is even lower. Then, the BE fit implies not hydrostatic equilibrium, but rather, instability. Finally, Ballesteros-Paredes et al. (2002) have found, over a sample of 120 cores on their 3 projections, that 50% of the projections can be fitted success fully by a BE profile, in spite of not being in hydrostatic equilibrium. This shows that fitting BE-like column density profiles to cores in numerical simulations is not an unambiguous test for hydrostatic equilibrium.

2. Cloud Formation and Destruction

The evidence reviewed in the last section that clouds have important fluxes of the physical quantities (mass, momentum, energy) through their boundaries, and

\[ 1 \] It is important to mention that the preceding discussion is not in contradiction with the fact that stars are objects in hydrostatic equilibrium within a turbulent medium, since they do not correspond to quasi-isothermal flows. In stars, energy is trapped since the opacity has increased, and the cooling time is about \(10^{10}\) times the free-fall time. In order for a core formed by a compression to reach equilibrium, the isothermalicity of the flow must be released. Under MC conditions, this requirement occurs until scales and densities of protostars are reached (Ballesteros-Paredes et al., 1999a).
that they have important time derivatives of their moment of inertia, suggests that they may be much short-lived than previously thought, in line with suggestions by, among others, Sasao (1973), Hunter (1979), Hunter et al. (1986), Verschuur (1991), Elmegreen (1993) Ballesteros-Paredes et al. (1999a), that clouds are turbulent density fluctuations.

As has been discussed in previous reviews (e.g., Elmegreen, 1993), it is most likely that there are more than a single mechanism for cloud formation. There is more or less agreement that the earlier models of collisional agglomeration of smaller ‘cloudlets’ by, e.g., Kwan (1979), Scoville and Hersh (1979), Cowie (1980), do not reproduce the observations (Blitz and Shu, 1980). In particular, in those models, the time required for building up a giant MC (∼ 100 Myr) is so long that it is difficult to either support a GMC against collapse, or avoid their disruption by the internal HII regions and SN explosions. In addition to the fact that there is not enough molecular material in the ‘chaff’ to allow the formation of GMCs via agglomeration (Blitz and Williams, 1999), the picture of ‘cloudlets’ flying ballistically might be inadequate, since clouds are not a collection of isolated entities of gas, but an interconnected network that has only been made to look like spheres due to the limitations of the observations (Scalo, 1990).

Within the context of a turbulent ISM, clouds may form by the convergence of turbulent flows at large scales. These might be probably produced by different instabilities (Parker, thermal, gravitational, or magnetorational [Sellwood and Balbus, 1999]), the passage of spiral density waves, swept up shells from SN remnants or simply the general action of global turbulence, where no single apparent mechanism is invoked, but the result of streams at different velocities that collide (see Elmegreen, 1990, 1993; Blitz and Williams, 1999 for reviews). An interesting alternative considered by Pringle et al. (2001) is that a large fraction (∼ 50%) of the interstellar medium may be in the form of (non-self gravitating) molecular gas which is too cold to be detected. In their picture, we can only observe the molecular gas that is illuminated by sufficiently nearby heating sources. It is compressed in spiral shocks and only there a substantial fraction of the gas becomes self-gravitating enough to initiate star formation. It is only at this point, they argue, that we are able to see it.

In any event, an important constraint that should be satisfied for any cloud formation model are the observed ages of newborn stars in MCs, since they are the most direct measurement of a time scale in MCs. The other time scale is the dynamical or crossing time, \( \tau \sim l/\Delta v \). Although it is applicable only in a statistical sense, there may be strong discrepancies when compared to the ages of stars. For example, for Taurus, \( l \sim 20 \) pc, \( \Delta v \sim 2 \) km s\(^{-1}\), the dynamical timescale is of the order of 10 Myr, while the ages of the young stars are only \( \sim 2 \) Myr (see, e.g., Ballesteros-Paredes et al., 1999b and references therein).

It is important to note that there is some controversy on the determination of ages in star-formation regions. For example, Palla and Stahler (2000, 2002), argue that nearby MC have been forming stars in the last 10 Myr or more, with a recent
burst of star formation. However, Hartmann (2002) argues that their conclusions are skewed by a statistically small sample of stars with masses larger than 1\(M_\odot\), and by biases in their birthline age corrections. He notes that the picture by Palla and Stahler (a) requires the last 1–2 Myr to be a special epoch for most MCs; (b) implies that most MCs are forming stars at extremely low rates, if any; and that (c) the apparently oldest stars are systematically higher in mass, implying that for most of a typical MC’s star-forming epoch, the Initial Mass Function was strongly skewed. Item (a) seems implausible, and items (b) and (c) are contradicted by observations (see Hartmann, 2002, and references therein). A more plausible explanation of the observations is that the ‘tail’ of older stars is really the result of including older foreground stars, as well as problems with the isochrones calibration in the higher mass stars.

Blitz and Williams (1999) argue that giant MC must live for some times 10 Myr based on the ages of stars in Orion quoted by Blaaw (1964). Nevertheless, more recent estimates of the stellar ages (Brown et al., 1994; Briceño et al., 2001) show that in the Orion OB1a association, which has \(\sim\) 10 Myr old stars, there is virtually no molecular gas associated. Instead, in Orion OB1b, which contains large amounts of gas, the stars are about 1 Myr old, a value close to the estimated for young stars in Taurus.

Hartmann et al. (2001) tabulate the ages of stars in 13 nearby star-forming regions. For those regions with stars older than \(\sim\) 5 Myr, there is no molecular gas associated, suggesting that the time scales for both cloud- and star-formation are shorter even than the dynamical time scale proposed by Elmegreen (2000).

The fact that several molecular regions exhibit synchronized star formation with ages of the newborn stars much smaller than the dynamical time suggests that some kind of external triggering must be involved. Vázquez-Semadeni et al. (1995), Ballesteros-Paredes et al. (1999b) and Harmann et al. (2001) suggest that global turbulence may play a crucial role. In their picture, large-scale flows powered by global events of star formation along the Galaxy may collide, form clouds and stars rapidly, and then dissipate. The idea is not new (Blaaw, 1964; Elmegreen and Lada, 1977; McCray and Kafatos, 1987), but although mechanisms like nearby HII regions in expansion, or SN events, are not discarded, all these processes feed the global turbulence, and thus no single mechanism need be directly responsible for the formation of any particular cloud complex.

How fast can MCs be formed by the general turbulence? Ballesteros-Paredes et al. (1999b) show that clouds can be produced rapidly (in few Myr) by the convergence of large-scale flows, evolving to high densities over scales of tens of parsecs nearly simultaneously. This is because the velocities involved are of the order of the velocity dispersion at the large scales (several km s\(^{-1}\)), rather than of the internal velocity dispersion of the clouds. Nevertheless, the exact cloud build-up time may depend on how much mass the streams are carrying, how strong the compression is, the rate of cooling of the compressed (shocked) region, the geometry of the compression, etc. Even with the typical ISM flow velocities \(\sim\) 10 km s\(^{-1}\), it can
take tens of Myr to accumulate enough mass from the diffuse interstellar medium ($n \sim 1\, \text{cm}^{-3}$) to form a MC complex. However, a necessary (though not sufficient) condition for the existence of molecular material in the solar neighborhood is that it have sufficient column density to effectively shield H$_2$ and CO from the dissociating ultraviolet radiation of the diffuse Galactic field. This requires a minimum column density in hydrogen atoms of roughly $10^{21}\, \text{cm}^{-2}$ (see Franco, 1993 and references therein). Thus, even if the process of building up material from diffuse H I takes a long time, the ‘life’ time of the MC in the solar neighborhood only begins once this minimum column density is attained (Hartmann et al., 2001).

An important point to note is that the column density needed to allow molecular gas to be formed is similar to that required for the MC to become self-gravitating, under solar-neighborhood conditions ($\lesssim 1\, \text{A}_\odot$). This may be the main reason why star formation is presently occurring in virtually all MC complexes of significant size within a kiloparsec from Sun (Hartmann et al., 2001), but the situation for the inner or outer galaxy may be quite different (Cox and Franco, 1986).

Concerning the destruction of clouds, studies of other star-forming regions in addition to Taurus (Hartmann, 2002, and references therein) in the solar neighborhood such as Cha I and IC 348 (Lawson et al., 1996; Herbig, 1998) also provide relatively little evidence for large populations of stars older than few Myr, especially when observational biases are eliminated. This suggests that the molecular gas may be dispersed also in a few Myr, a time scale consistent with the cluster survey results of (Leisawitz et al., 1989).

Several mechanisms for cloud-disruption have been proposed: SN explosions, the action of massive stars (UV ionizing radiation and/or winds), the lowering of shielding by an expansion of the cloud, the action of internal and/or external turbulence, etc. As pointed out by Franco et al. (1994), while SN explosions are the products of late stages of evolution, and take some time (6 Myr or more) to be ‘turned on’, massive stars on their main sequence may power the clouds almost immediately. Thus, even if SN explosions were the main mechanism powering global turbulence in the ISM (see MacLow, this volume), it is likely that the main agent disrupting clouds is the massive OB stars. This view has been recently supported by Matzner (2002), who has argued that the most efficient mechanism for cloud destruction is photoionization in H II regions, even considering the combined effects of winds (from proto-, main-sequence and evolved stars) and SNe. Once HII regions are created, their expansion is responsible for ionizing and photodissociating all the environmental gas.

At this point it is important to mention that a comparison between observational data and numerical simulations with a star formation prescription in which stars are formed in the densest regions (Vázquez-Semadeni et al., 1997) supports the view that clouds are dispersed by OB stars. Indeed, consider the case of Orion OB1 (Figure 1a), mentioned before. OB1a region contains ~10 Myr-old stars but no molecular gas. Instead, the OB1b association contains 1 Myr-old stars, and large amounts of gas. A similar situation is found in the simulations (Figure 1b), where
the energy input is due to ‘O stars’ that last 6 Myr. As can be seen, the older, 5 – 8 Myr stars\(^2\) (smaller crosses), are 10 – 20 pc away from the gas.

Other mechanisms may also help in the dispersal of the clouds, and contribute to the low star-formation efficiency, such as ejections from massive stars (Withworth, 1979) and winds and outflows (e.g., Norman and Silk, 1980; Leisawitz et al., 1989; Matzner and McKee, 2000). However, these are not considered as the main mechanisms because they are considerably less energetic than the HII regions and/or SN explosions. Recently, two other mechanisms have been proposed (although not explored in detail): the lowering of shielding (Hartmann et al., 2001), and the same large-scale streams that creates the clouds, may destroy them (Ballesteros-Paredes et al., 1999b). In the first case, if clouds like Taurus (with a mean column density that corresponds to an \(A_V \sim 1 – 2\), Arce and Goodman, 1999) suffer an expansion of surface area by a factor of 2 or 3, the column density will be reduced by the same factor, allowing the destruction of molecular gas, with the consequent increase of temperature and, thus, of the Jeans length. In the second case, although a small fraction of the mass in clouds formed by turbulence may be considerably self-gravitating and susceptible for collapse and star formation, most of the mass may be (marginally) unbound and thus easily dispersed (Shadmehri et al., 2001; Vázquez-Semadeni et al., 2002a). These mechanisms, as well as the first mentioned, require further study, in order to quantify their efficiency in disrupting less massive clouds as, e.g., Taurus, where no massive stars or HII regions are available to contribute to the dispersal. In any event, rapid dispersal of gas is required to avoid extended periods of star formation, as stellar ages suggest.

\(^2\) Note that stars older than 6 Myr are fossils, and they are not contributing anymore to the dispersal of the parent cloud.
3. Conclusions

We have discussed the implications of the Virial theorem on MCs’ lifetimes. Consisting in two dimensions of spatial information, one dimension of velocity information, and no time evolution information, observations can not probe that clouds are or not in Virial equilibrium. Thus, numerical simulations can show important qualitative features, even if details were missing or incorrect. Numerical works have shown that clouds are not in Virial equilibrium, that there is strong exchanges of mass, momentum and energy with their environment, that time derivatives are non-negligible, and that surface terms can not be neglected, being always comparable to the respective volumetric term. Nevertheless, these simulations show equipartition between the self-gravity and the internal energies of the clouds, just as observations do (e.g., $GM/R \sim \delta v^2$).

If time derivatives and surface terms in the Virial theorem are important, then clouds (and cores) must be transient. We discussed that several mechanisms may be responsible for the formation of clouds, with some emphasis on the global effects of multiscale turbulence. This picture is consistent with recent estimations of ages of stars associated to molecular gas shown in the literature. Regarding destruction of MCs, it is favored the scheme in which HII regions have enough power, and act before SN, to be the dominant factor of cloud dispersal. Nevertheless, some other mechanisms may operate, in order to understand the lack of extended periods of star formation in low-mass starforming regions as Taurus.

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References

MOLECULAR CLOUDS: FORMATION AND DISRUPTION


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