Gravity or turbulence? Velocity dispersion-size relation

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ABSTRACT

We discuss the nature of the velocity dispersion versus size relation for molecular clouds. In particular, we add to previous observational results showing that the velocity dispersions in molecular clouds and cores are not purely functions of the spatial scale but involve surface gas densities as well. We emphasize that hydrodynamic turbulence is required to produce the first condensations in the progenitor medium. However, as the cloud is forming, it also becomes bound, and gravitational accelerations dominate the motions. Energy conservation in this case implies $|E_g| \sim E_k$, in agreement with observational data, and providing an interpretation for two recent observational results: the scatter in the δv -R plane, and the dependence of the velocity dispersion on the surface density $\delta v^2/R \propto \Sigma$. We argue that the observational data are consistent with molecular clouds in a state of *hierarchical and chaotic gravitational collapse*, i.e. developing local centres of collapse throughout the whole cloud while the cloud itself is collapsing, and making equilibrium unnecessary at all stages prior to the formation of actual stars. Finally, we discuss how this mechanism need not be in conflict with the observed star formation rate.

Key words: turbulence – stars: formation – ISM: clouds – ISM: general – ISM: kinematics and dynamics.

1 INTRODUCTION

Almost 30 yr ago, Larson (1981) suggested that two scaling relations exist for molecular clouds, one for the velocity dispersion δv and the other for the mean density ρ . These have the form

$$\rho \propto R^{\alpha},$$
(1)

$$\delta v \propto R^{\beta},$$
 (2)

where *R* is the size of the cloud. The most commonly accepted values of the exponents are¹ $\alpha \sim -1$ and $\beta \sim 0.5$ (see Solomon et al. 1987; Blitz 1993; Ballesteros-Paredes et al. 2007; McKee & Ostriker 2007, and references therein). The first relation implies that the mean column density of the gas, $\Sigma = \rho R$, is roughly constant for the whole ensemble of clouds. This result has been challenged by various authors; for instance, Kegel (1989) pointed out that it may be the result of various selection effects. Scalo (1990) showed that the study by Solomon et al. (1987) was sensitive only to a limited dynamical range of column densities. Moreover, Vazquez-Semadeni et al. (1997) used numerical simulations of a 1-kpc² piece

of the Galaxy to argue that the mean density–size relation does not hold when no detectability limitations exist. Ballesteros-Paredes & Mac Low (2002) used three-dimensional simulations to confirm that clouds can have different mean densities and that the density–size relation appears when clouds are observed with particular tracers, since they must have at least a minimum column density in order to be detectable.

On the other hand, the velocity-size relation (equation 2) has often been assumed to be real. One reason for this is probably that the relation is similar to what might be expected from studies of fluid turbulence: the expected value for incompressible turbulence is $\beta \sim 1/3$, while a turbulent fluid dominated by shocks might exhibit $\beta \sim 1/2$ (e.g. Elmegreen & Scalo 2004; McKee & Ostriker 2007, and references therein). As the interstellar medium is highly compressible, and subject to strong shocks of stellar winds, supernovae (SNe), spiral arms, etc., one might then expect that the velocity dispersion-size scaling relation with $\beta = 1/2$ should be valid, and, of course, supersonic turbulent simulations, as well as analytical calculations of molecular clouds performed over the last decade, have supported the idea of a velocity dispersion-size relation with $\beta \sim 1/2$ (e.g. Vazquez-Semadeni et al. 1997; Padoan & Nordlund 1999; Ballesteros-Paredes, Vázquez-Semadeni & Scalo 1999b: Ballesteros-Paredes & Mac Low 2002: Padoan & Nordlund 2002; Krumholz & McKee 2005; Field, Blackman & Keto 2008, etc).

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¹ Note that the original values for the exponents reported by Larson (1981) are $\alpha \sim -1.1$ and $\beta \sim 0.38$.

However, if Larson's original data set, as well as that of Solomon et al. (1987), was limited in the range of column densities observed, then why should only one of these correlations be affected but not the other one? In principle, one may expect that the velocity dispersion– size relation is also implicitly a result for a limited range of column densities.

Recently, Heyer et al. (2009) observed an ensemble of molecular clouds with the 14-m FCRAO telescope. Because present data have much better sensitivity, as well as spectral and angular resolution, molecular clouds observed with the BU-FCRAO Galactic Ring Survey (Jackson et al. 2006) exhibit a much larger dynamic range in column density than was possible in the 1980s. Using that data set, Heyer et al. (2009) found that the velocity dispersion does not depend simply on size scale, but on the square root of the column density as well. They went on to point out that the revised relation,

$$\delta v \propto \Sigma^{1/2} R^{1/2},\tag{3}$$

was that to be expected for clouds in gravitational *equilibrium*. In addition, while the derived masses for the clouds were a factor of a few lower than expected for virial equilibrium, Heyer et al. (2009) stated that uncertainties in their mass estimates still allowed for consistency with equilibrium states. Larson (1981) actually came to a similar conclusion even with his limited data set; he argued that the clouds are mostly gravitationally bound and in approximate virial equilibrium. However, since the clouds' column densities vary by over three orders of magnitude (from $\sim 10^{21}$ cm⁻² in the most diffuse clouds to $\sim 10^{24}$ cm⁻² for infrared dark clouds), the simple form of the velocity–size relation, equation (2), may not be the most appropriate form for molecular clouds.

To further explore the correlation between the velocity dispersion and size for molecular cloud cores, in Section 2, we compile recent data from the literature in order to show that a unique trend for the scaling of the velocity dispersion with size does not appear to exist, specifically when we include recent sensitive observations of massive cores. Instead, relation (3) seems to hold in all cases.

The question is then, what is the origin of the velocity-surface density-radius correlation? In the past, it has been proposed that this relationship arises from a condition of hydrostatic equilibrium applying to the clouds and dense clumps (Elmegreen 1989; McKee & Tan 2003; Field, Blackman & Keto 2010). In this case, it is assumed that the clouds are confined by an external bounding pressure, which is estimated from the clouds' column density, and that the role of the turbulent motions within the clouds is to provide support. However, as summarized by Ballesteros-Paredes et al. (1999b) and Ballesteros-Paredes (2006), the complex nonlinear, large-scale and anisotropic nature of turbulent motions implies that they do not necessarily provide support, but rather cause continuous morphing and reshaping of molecular clouds, and contribute to, or perhaps are even driven by, the clouds' gravitational collapse (Vázquez-Semadeni et al. 2008). In particular, it is difficult to see how such an irregular and locally anisotropic velocity field could 'know' how to adjust the magnitude and orientation of the turbulent motions to maintain clouds in approximate equilibrium for several free-fall times. Indeed, it is difficult to argue that global equilibrium is maintained, given evidence for age spreads in stellar populations that are smaller than the lateral crossing times of the clouds (Ballesteros-Paredes, Hartmann & Vázquez-Semadeni 1999a; Hartmann, Ballesteros-Paredes & Bergin 2001). As we discuss in the present contribution, the observed correlations can be explained as long as the velocity dispersions result from gravitational acceleration, without requiring equilibrium at any stage prior to the formation of an actual star.

2 VELOCITY DISPERSION VERSUS SIZE RELATION

Although it is frequently argued that molecular clouds and their cores usually exhibit a relation like equation (2), after the study by Caselli & Myers (1995), and probably more clearly by Plume et al. (1997), it became somehow recognized that massive cores may exhibit a shallower slope than the frequently quoted $\delta v \propto r^{1/2}$. Moreover, the various available data sets have not been plotted all together.

In Fig. 1, we plot the velocity dispersions as a function of size for the dense cores given by Caselli & Myers (1995), Plume et al. (1997), Shirley et al. (2003), Gibson et al. (2009) and Wu et al. (2010). For comparison, we have included also the data points of the original work of Larson (1981), as well as the recent data by Heyer et al. (2009), neither of which focused particularly on dense massive cores. The dotted lines in this figure represent Larson's fit to his data, that is,

$$\left(\frac{\delta v}{\mathrm{km}\,\mathrm{s}^{-1}}\right) = 1.1 \left(\frac{L}{\mathrm{pc}}\right)^{0.38}.\tag{4}$$

We observe that, while in general terms, the typical CO clouds observed by Heyer et al. (2009) lie close to Larson's relation, this is clearly not the case for the dense, massive cores, which exhibit large velocity dispersions for their relatively small sizes. Although the deviation is only marginal for the Orion cores observed by Caselli & Myers (1995), it is clearer for the more massive compact cores reported by the rest of the data sets.

In Fig. 2, we plot the 'Heyer relation', $\delta v/r^{1/2}$ versus surface density Σ . Unfortunately, the observations of massive dense cores, particularly from infrared dark clouds, are very recent, and only few cores have independent mass estimations. From the list of references given above, only that by Heyer et al. (2009) and Gibson et al. (2009) lists the masses of their observed cores independent of the virial mass, and thus, only these data can be plotted. In this figure, the data points from the samples by Heyer et al. (2009) and Gibson et al. (2009) are denoted by H and G, respectively. The long-dashed and dotted lines, respectively, represent the loci of structures in virial equilibrium and structures undergoing free-fall. From this figure, it is clear that the massive cores from Gibson et al. (2009) span over two orders of magnitude in column density, from ~ 100 to a few times $10^4 \text{ M}_{\odot} \text{ pc}^{-2}$, the latter being a factor of 10 larger than the maximum column density in the Heyer et al. (2009) data. We note that the entire data set is seen to be reasonably well fitted by a relation of the form proposed by Heyer and in fact, at face value, seems to agree better with the free-fall regime than with virial equilibrium.

It is important to note that the free-fall relation actually implies *larger* velocity dispersions than the virial equilibrium one, contrary to the very common interpretation that velocities higher than virial imply that the clouds are unbound. From this discussion, we see that they can mean chaotic infalling motions instead.

3 DISCUSSION

3.1 The δv -*R* relationship, a consequence of the role of gravity in the formation and evolution of molecular clouds

In order to understand the nature of the δv -R relation, it is important to understand how molecular clouds are formed and how they evolve.



Figure 1. Velocity dispersion–size space for observed cores. Data compiled from Larson (1981), Caselli & Myers (1995), Plume et al. (1997), Shirley et al. (2003), Gibson et al. (2009), Heyer et al. (2009) and Wu et al. (2010). Note that, while large CO clouds from the survey by Heyer et al. (2009) exhibit the typical Larson relationship, dense massive cores are located above this relationship. All together (lower right-hand panel), the data do not exhibit a relation between the velocity dispersion and size.



Figure 2. Heyer's relation $(\delta v/r^{1/2}$ versus surface density Σ) for the clouds reported in Heyer et al. (2009) and Gibson et al. (2009). Note that the massive cores follow the tendency showed by Heyer et al. (2009), but they are at the large column density end of that relationship, ranging from 100 to ~25000 M_{\odot} pc⁻².

In the last few years, a number of authors have supported the idea that molecular clouds are formed out of atomic gas when large-scale streams collide at transonic speeds² (e.g. Ballesteros-Paredes et al. 1999a,b). The collision non-linearly triggers thermal instability in the post-shock gas (Hennebelle & Pérault 1999) with the result that the gas cools rapidly, producing a dense, cold, turbulent cloud (Walder & Folini 1998; Koyama & Inutsuka 2002; Heitsch et al. 2005, 2006; Vázquez-Semadeni et al. 2006), which soon becomes Jeans unstable (Vázquez-Semadeni et al. 2007; Heitsch et al. 2008). Since the interstellar medium, rather than homogeneous, is highly structured, such shocked, cold, dense medium will naturally produce clumps (Bonnell et al. 2006). As the whole cloud collapses, the column density increases rapidly, allowing the formation of molecular gas (e.g. Heitsch & Hartmann 2008; Glover et al. 2010). From this point of view, molecular clouds are in a global state of collapse,

² These ideas have been developed specifically for understanding star formation (SF) in the solar neighbourhood, where most of the gas is atomic. In other regions, such as the molecular ring, large-scale flows in molecular gas can also produce dense star-forming regions.

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with an internal distribution of free-fall times due to the fluctuations in the density field induced by the initial turbulence (Burkert & Hartmann 2004; Vázquez-Semadeni et al. 2006; Heitsch & Hartmann 2008). Note that this does *not* necessarily mean that the entire cloud is collapsing along all dimensions; for example, in the toy model of the Orion A cloud by Hartmann & Burkert (2007), the angular momentum of the cloud prevents collapse along the long dimension.

In this scenario, supersonic motions in molecular clouds are driven by gravitational energy as the clouds proceed to collapse, a situation that has been supported by Heitsch, Ballesteros-Paredes & Hartmann (2009), who show that the synthetic line profiles observed in numerical simulations of the process resemble those in observations, for example, the magnitude of the velocity dispersion of ¹³CO line profiles, or the (small) core-to-core velocity dispersion.

The key point, however, was emphasized by Vázquez-Semadeni et al. (2007) who showed that the kinetic and gravitational energies of the collapsing cloud develop a virial-like relationship in complex gravitationally collapsing clouds, in which the absolute value of the kinetic energy is very close to that of the gravitational energy (see fig. 8 in Vázquez-Semadeni et al. 2007).³ In other words, the 'virial' relation between the kinetic and gravitational energy, rather than being an indicator of true virial *equilibrium*, simply shows the importance of gravity in driving much of the non-thermal motions.

Field et al. (2008) have advanced a model of a 'gravitational cascade', which essentially captures the mechanism observed in the simulations. Their model is analogous to a turbulent cascade, in which the quantity being cascaded is mass rather than kinetic energy, and the main driver is gravity at all scales. In their model, these authors propose that the contracting motions are somehow randomized, so that the kinetic energy released by the collapse is converted into quasi-isotropic motions and virial quasi-equilibrium can be established at every scale (see their section 3). Such virial equilibrium states require that the mass fragments are bound by an external pressure (Elmegreen 1989; McKee & Tan 2003; Field et al. 2010). In the latter paper, the authors write the virial equilibrium equation for a non-magnetized cloud of gas of mass *M* and radius *R* in terms of its mass surface density $\Sigma = M/R^2$ as

$$\frac{\delta v^2}{R} = G\Sigma - \frac{4\pi}{\Sigma} P_{\text{ext}},\tag{5}$$

where the first term in the right-hand side corresponds to the gravitational energy and the second one is due to the external pressure acting over the surface of the cloud. However, the successive virializations suggested by Field et al. (2008) will not occur, if cloud lifetimes are too short, as pointed out by Bonnell et al. (2006).

More importantly, a cloud undergoing collapse does not need to be confined by an external pressure. Instead, the internal pressure increases together with the density, and once the collapse has advanced sufficiently, the external pressure becomes negligible. Indeed, as mentioned above, these regions within molecular clouds are known to have much larger thermal pressures than the ISM mean (e.g. Blitz 1993). Thus, rather than virial equilibrium, the relevant principle here is that the total energy of the system ($E_g + E_k$) is



Figure 3. Velocity dispersion–size space. The lines are the loci of cores and clumps at constant column density, if the velocity dispersion is of gravitational origin, such that equation (6) is valid.

conserved. In this case, the ratio $\delta v^2/R$ is given by

$$\frac{\delta v^2}{R} = 2G\Sigma. \tag{6}$$

Moreover, if the collapsing scenario applies to all scales within molecular clouds, we expect equation (6) to be valid not only for massive cores, but also for molecular clouds in general. Thus, it seems unavoidable to think that the molecular cloud supersonic linewidths, rather than being hydrodynamical turbulent motions, are what we refer to as *hierarchical and chaotic gravitational collapse*, that is, the local gravitational contractions occurring throughout the whole cloud, which, furthermore, is itself collapsing.⁴ In other words, the kinetic energy gained during the hierarchical collapse must come from the gravitational energy released and therefore develops a virial-like relation, except that the velocity dispersion is given by equation (6) rather than by the virial relation $\delta v^2/R = G\Sigma$.

The assumption of gravity driving the chaotic motions in multiple local centres of collapse, and thus developing a pseudo-virial state (equation 6), implies that massive, compact cores should develop larger velocity dispersions for larger column densities ($N \sim$ $10^{23}-10^{25}$ cm⁻², Shirley et al. 2003; Gibson et al. 2009; Wu et al. 2010). In Fig. 3, we show, in the velocity dispersion-size space, lines of constant column density according to equation (6), the locus of the Larson (1981) relation, equation (4) and the region where the massive cores are located. From this figure, we note that typical local clouds with mean column densities of 10^{21} – 10^{22} cm⁻² will necessarily be close to Larson's relation, as observed in the data (e.g. Larson 1981; Heyer et al. 2009). Column densities far below this relation will be unable to self-shield against background ultraviolet radiation (e.g. Hartmann et al. 2001) and will be rapidly dissociated or do not form at all. However, as discussed previously, column densities far above Larson's relation do exist - in the recently massive compact cores, which occupy the locus $0.1 \le r/pc \le$ $1, 1 \le \delta v / \text{km s}^{-1} \le 10$ (see Figs 1 and 3) – and, although they do not fall on Larson's relation, they do fall on Heyer's.

Larson (1981) argued that supersonic hydrodynamics must be important in cloud structure and that the clouds cannot have formed

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³ Note that in Vázquez-Semadeni et al. (2007), the absolute value of the gravitational energy is a few times that of the kinetic energy. However, in that paper, the latter energy was computed exclusively for the dense gas, while, for simplicity, the gravitational energy was computed for the whole numerical box.

⁴ Note that the resulting motions of such hierarchical and chaotic gravitational collapse is, in a way, supersonic turbulence. However, rather than being the physical ingredient that opposes gravity, it is a consequence of gravity itself.

'by simple gravitational collapse'. The model clouds by Vázquez-Semadeni et al. (2007) and Heitsch & Hartmann (2008) do indeed exhibit important effects of hydrodynamic turbulence, especially in early stages of formation. However, hierarchical and chaotic gravitational collapse comes to dominate at late stages; it is just not 'simple', because the geometry is complicated, with several local centres of collapse within the parent cloud that is contracting as a whole, giving rise to chaotic density and velocity fields. The local collapse occurs because the initial turbulence, in combination with strong radiative losses, induces non-linear density fluctuations that have shorter free-fall times than the parent cloud (Heitsch & Hartmann 2008).

The scenario of hierarchical and chaotic gravitational collapse is similar in spirit to the classic notion of gravitational fragmentation (Hoyle 1953), except that it takes place on a substrate populated with non-linear density fluctuations produced by the initial turbulence. This eliminates the simultaneity of the collapses that would be expected in a uniform medium. In this case, the driving force is gravity, as opposed to previous scenarios, where the confining force for the (hydrostatic) clouds was the pressure external to the clouds (e.g. Elmegreen 1989; McKee & Tan 2003; Field et al. 2010). It is interesting to note, however, that in those works, the presence of such a confining pressure was assumed, and diverse mechanisms had to be devised in order to attain the necessary high pressures, such as the weight of an atomic component (Elmegreen 1989) or a recoil pressure from the photodissociation regions around the clouds (Field et al. 2010). In our scenario, such confining pressure does not exist, and the large internal pressure of the clouds is simply a consequence of the ongoing collapse.

3.2 Avoiding the star formation rate conundrum

The idea that giant molecular clouds (GMCs) and their substructure may be in a state of gravitational collapse is not new. In fact, it was the first proposed explanation for the observed supersonic linewidths (Goldreich & Kwan 1974). However, as it is well known, it was quickly deemed untenable by Zuckerman & Palmer (1974), who argued that if all molecular gas in the Galaxy were in a state of free-fall, the star formation rate (SFR) would be of the order of M_{mol}/t_{ff} , where M_{mol} is the total molecular gas mass in the Galaxy and t_{ff} is the mean free-fall time of the molecular gas. This results in an SFR roughly 100 times larger than the observed value of a few M_{\odot} yr⁻¹.

This simple reasoning, however, does not necessarily apply for real molecular clouds, since it neglects their complex, highly fragmented nature of density distribution. Because of the existence of a wide distribution of local free-fall times in a GMC, the densest clumps collapse significantly sooner than the GMC at large and begin forming stars before the bulk of the GMC has collapsed, as observed in simulations (e.g. Vázquez-Semadeni et al. 2007; Heitsch et al. 2008; Banerjee et al. 2009; Vázquez-Semadeni et al. 2010). The feedback from the stellar products (in the form of outflows, winds, ionizing radiation and SNe) can then interrupt the SF process before it exhausts the entire mass of the GMC. Furthermore, since it is well known that most of the molecular gas mass is in the large-scale structures, this implies that the SF efficiency will remain small, because the stellar activity originates from the objects that collapse first, which contain the minority of the mass. Indeed, numerical simulations of GMC formation and evolution, including self-consistent stellar feedback by Vázquez-Semadeni et al. (2010), show that the SF efficiency can be maintained at realistic values throughout the evolution of the cloud, still within the context of large-scale gravitational contraction. As mentioned above, the youth and strong coevality of stellar populations in the clouds suggest that stellar feedback acts quickly to suppress SF at any given location, and acts to either relocate it, for a next generation of SF at a different location, or even to completely disperse a cloud. Although the details of this process still need to be refined, it is clear that the SF conundrum does not need to apply for GMCs in general.

4 CONCLUSIONS

In the present contribution, we have discussed the nature of the velocity dispersion-size relationship. We showed that recent observational results do not follow the standard Larson (1981) velocity dispersion-size relation. Instead, (i) massive cores occupy the locus defined by $0.1 \le R/pc \le 1$; $1 \le \delta v/km s^{-1} \le 10$ and (ii) rather than a single $\delta v - R$ relation, the entire data set for which independent mass estimates are available seems to follow the Heyer et al. (2009) scaling, $\delta v \propto \Sigma^{1/2} R^{1/2}$. We showed that these results are consistent with molecular clouds in a process of hierarchical and chaotic gravitational collapse, that is, molecular clouds collapsing as a whole, while, at the same time, their cores collapsing locally, creating a complex supersonic velocity pattern that is, however, not fully random, as in the standard notion of turbulence, but rather contains a dominant globally contracting mode. As a consequence, this turbulence cannot oppose the contraction, but rather feeds from it.

We emphasized that, although hydrodynamic turbulence in the warm ISM must play a role in producing the initial molecular cloud and its condensations (Clark & Bonnell 2005), once gravity dominates the motions at late stages, pseudo-virial relationships seen in the data naturally result. Thus, it is not necessary (let alone likely) that clouds and their cores are in pressure equilibrium with the external medium, nor is it necessary to resort to some unspecified mechanism that can accurately keep massive clouds with complex, non-spherical and clumped density distributions in an approximate equilibrium for many crossing times.

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