WHAT SHAPES THE STRUCTURE OF MOLECULAR CLOUDS: TURBULENCE OR GRAVITY?

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ABSTRACT

We revisit the origin of Larson’s scaling relations, which describe the structure and kinematics of molecular clouds, based on recent observations and large-scale simulations of supersonic turbulence. Using dimensional analysis, we first show that both linewidth–size and mass–size correlations observed on scales 0.1–50 pc can be explained by a simple conceptual theory of compressible turbulence without resorting to the often assumed virial equilibrium or detailed energy balance condition. The scaling laws can be consistently interpreted as a signature of supersonic turbulence with no need to invoke gravity. We then show how self-similarity of structure established by the turbulence breaks in star-forming clouds through development of gravitational instabilities in the vicinity of the sonic scale, \( \ell_s \sim 0.1 \) pc, leading to the formation of prestellar cores.

Subject headings: stars: formation — ISM: structure — turbulence — methods: numerical

1. INTRODUCTION

Larson [1981] established that for many molecular clouds (MCs) their internal velocity dispersion, \( \sigma_u \), is well correlated with the cloud size, \( L \), and mass, \( M \). Since the power-law form of the correlation, \( \sigma_u \propto L^{3/8} \), and the power index, 0.38 \( \sim 1/3 \), were similar to the Kolmogorov [1941] law of incompressible turbulence (K41), he suggested that the observed nonthermal linewidths may originate from a “common hierarchy of interstellar turbulent motions.” Larson also noticed that the clouds appear mostly gravitationally bound and in approximate virial equilibrium, as there was a close positive correlation between the velocity dispersion and mass of the clouds, \( \sigma_u \propto M^{0.20} \), but suggested that these structures “cannot have formed by simple gravitational collapse” and should be at least partly created by supersonic turbulence. This seminal paper preconceived many important ideas in the field and strongly influenced its development for the past 30 years.

Solomon et al. [1987] confirmed Larson’s study using observations of \(^{12}\)CO emission with improved sensitivity for a large uniform sample of 273 nearby clouds. Their linewidth–size relation, \( \sigma_u = 1.0 \pm 0.15^{0.05} \) km s\(^{-1}\), however, had a substantially steeper slope than Larson’s, reminiscent of that for clouds in virial equilibrium
\[\sigma_u = (\pi G \Sigma)^{1/2} / R^{1/2},\] (1)

since the Solomon et al. [1987] clouds had approximately constant molecular gas surface density, \( \Sigma \), independent of their radius. The surface density–size relation, also known as the third Larson’s law, can be derived eliminating \( \sigma_u \) from his first two relations: \( \Sigma \propto mL^{-2} \propto L^{0.38}/0.20^{-2} \propto L^{0.1} \). Assuming that \( \Sigma = \text{const} \) for all clouds, Solomon et al. [1987] evaluated the “X-factor” to convert the luminosity in \(^{12}\)CO \((1-0)\) line to the MC mass. The new power index value \( \sim 0.5 \) ruled out Larson’s hypothesis that the correlation reflects the Kolmogorov law \( \sigma_u \propto L^{1/3} \). In the absence of robust predictions for the velocity scaling in supersonic turbulence (cf. Passot et al. 1988), simple virial equilibrium-based interpretation of linewidth–size relation appealed to many in the 1980s.

Since then views on this subject remain polarized, while it is still uncertain whether gravity or turbulence (or magnetic fields) govern the dynamics of MCs. For instance, Ballesteros-Paredes et al. [2011a,b] argue that MCs are in a state of “hierarchical and chaotic gravitational collapse,” while Dobbs et al. [2011] believe that GMCs are “predominantly gravitationally unbound objects.” Heyer & Brunt [2004] found that the scaling of velocity structure functions (SFs) of 27 GMCs is nearly invariant, \( S_1 (u, \ell) \equiv \langle |u_\ell| \rangle = u_0 \ell^{0.56 \pm 0.02} \), for cloudy structures of size \( \ell \in [0.03, 0.50] \) pc. In the mean time, numerical simulations of supersonic isothermal turbulence returned very similar inertial range scaling exponents for the first-order velocity SFs \( S_1 (u, \ell) \propto \ell^\zeta \) with \( \zeta = 0.53 \pm 0.02 \) and \( 0.55 \pm 0.04 \) for longitudinal and transverse SFs, respectively, see Fig. 1 and Kritsuk et al. 2007a). The rms sonic Mach number, \( M_s = 6 \), used in these numerical experiments is characteristic of MC size scale \( \ell \approx 2 \) pc, i.e. right in the middle of the observed scaling range. The simulations indicated that the velocity scaling in supersonic regimes deviates strongly from Kolmogorov’s predictions for fluid turbulence. This result removes one of the Solomon et al. [1987] arguments against Larson’s hypothesis of turbulent origin of the linewidth–size relation. Indeed, the scaling exponent of \( 0.50 \pm 0.05 \) measured by Solomon et al. [1987] for whole clouds and a more recent and precise measurement \( 0.56 \pm 0.02 \) by Heyer & Brunt [2004] that includes cloud substructure both fall right within the range of expected values for

1 We deliberately keep the original notation used by different authors for the cloud size (e.g., the size parameter in parsecs, \( L \)= D tan(\( \theta/\pi \)) \); the maximum projected linear extent, \( L \); the radius, \( R = \sqrt{A/\pi} \), defined for a circle with area, \( A \), equivalent to that of cloud) to emphasize ambiguity and large systematic errors in the cloud size and mass estimates due to possible line-of-sight confusion, ad hoc cloud boundary definitions [Heyer et al. 2009], and various X-factors involved in conversion of a tracer surface brightness into the \( \text{H}_2 \) column density.

2 The lengths entering this relation are the characteristic scales of the PCA eigenmodes, therefore they may differ from the cloud sizes defined in other ways [McKee & Ostriker 2007].
supersonic isothermal turbulence at relevant Mach numbers.\footnote{Note that the distinction between scaling “inside clouds” and “between clouds” often used in observational literature is spurious because clouds are not isolated entities on scales of interest (e.g., Henriksen & Turner 1984).}

More recently, Heyer et al. (2009) used observations of a lower opacity tracer, $^{13}$CO, in a sample of 162 MCs with improved angular and spectral resolution to reveal systematic variations of the scaling coefficient, $\theta_0$, in Equation (2) with $L$ and $\Sigma$. Motivated by the concept of clouds in self-gravitating equilibrium, they introduced a new scaling coefficient $\theta'_0 \equiv \langle |\Delta u|\rangle^{-1/2} \propto \Sigma^{0.5} L^{-3}$. This correlation would indicate a departure from “universality” for the velocity SF scaling (2) and compliance with the virial equilibrium condition (1).

An alternative formulation of the original Larson’s third law, $m \propto L^{3/2}$, implied a hierarchical density structure in MCs. Such concept was proposed 60 years ago by van Hoerner to describe a complicated statistical mixture of shock waves in highly compressible interstellar turbulence (von Hoerner 1951; von Weizsäcker 1951). Von Hoerner pictured density fluctuations as a hierarchy of interstellar clouds, analogous to eddies in incompressible turbulence. MC observations indeed reveal a pervasive fractal structure in the interstellar gas that is interpreted as a signature of turbulence (Falgarone & Phillips 1991; Elmegreen & Falgarone 1996; Roman-Duval et al. 2010). The most recent result for a sample of 580 MCs, which includes the Solomon et al. (1987) clouds, shows a very tight correlation between cloud radii and masses,

$$m(R) = (228 \pm 18 M_\odot) R^{2.36\pm0.04},$$

for $R \in [0.2, 50]$ pc (Roman-Duval et al. 2010). The power-law exponent in this relation is simply the mass dimension of the clouds, $d_m \approx 2.36$, which corresponds to a “spongy” medium organized by turbulence into a multiscale pattern of clustered corrugated shocks (Kritsuk et al. 2006). Direct measurements of $d_m$ in high-resolution three-dimensional simulations of supersonic turbulence give the inertial sub-range values in excellent agreement with observations: $d_m = 2.39 \pm 0.01$ (1024$^3$ grid cells, Kritsuk et al. 2007a) and 2.28 $\pm$ 0.01 (2048$^3$ cells, Fig. 2), depending on details of forcing (Kritsuk et al. 2010). Note, that $d_m \approx 2.36$ implies $\Sigma \propto mL^{2} \propto L^{0.36}$, thus the observed mass–size correlation does not support the idea of a universal mass surface density of MCs. Meanwhile, positive correlation of $\Sigma$ with $L$ removes theoretical objections against the third Larson’s law outlined above.

With $d_m \approx 2.36$, the power-law index in the linewidth–size relation compatible with the virial equilibrium condition (1), $\zeta_{\text{vir}} = (d_m - 1)/2 \approx 0.68$, is still reasonably close to the scaling exponent $\zeta_1 \approx 0.56$ in Eq. (1), even if one assumes $\theta_0 = \text{const}$ (see §3 below). Thus we cannot immediately exclude the possibility of virial equilibrium (or kinetic/gravitational energy equipartition, see Ballesteros-Paredes 2006) across the scale range of up to three decades based on the available observations alone. At the same time, we have seen that the two classes of observed correlations (e.g., linewidth–size and mass–size) are readily reproduced in simulations without self-gravity (Kritsuk et al. 2011b). In this sense, non-gravitating turbulence is self-sufficient at explaining the observations. Hence, following Occam’s razor, it is not necessary to invoke gravity. Meanwhile, in turbulence simulations with self-gravity, the velocity power spectra do not show any signature of ongoing core formation, while the density and column density statistics bear a strong gravitational signature on all scales (Collins et al. 2012). What is the nature of this apparent “conspiracy” between turbulence and gravity in MCs? Why do structures in MCs appear gravitationally bound when they might not be?

In this Letter we use a simple conceptual theory of supersonic isothermal turbulence to show that scaling exponents in the linewidth–size and mass–size relations are connected, i.e. one can be derived from the other. In §2 we briefly introduce the concept of compressible cascade and discuss potentially universal relations. In §3 we derive the surface density–size and $\Sigma \propto mL^{2}$ relations in several different ways and demonstrate consistency with observations and numerical models. §4 deals with the effects of self-gravity on small scales in star-forming clouds, and discusses the origin of the observed mass-size relation for prestellar cores. Finally, in §5 we formulate our conclusions and emphasize the statistical nature of the observed scaling relations.

2. WHAT’S UNIVERSAL AND WHAT’S NOT

In turbulence research, universality is usually defined as independence on the particular mechanism by which the turbulence is generated (e.g., Frisch 1995). Following this convention, the non-universal nature of scaling relation (2) can be readily understood. Indeed, any scaling law for compressible

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Scaling of the first-order transverse (green) and longitudinal (red) velocity SFs in a simulation of isothermal supersonic turbulence with $M_s = 6$ (Kritsuk et al. 2007a). $\Delta$ is the grid spacing.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Compensated scaling of the mass, $m$, with size $L$ in a 2048$^3$ simulation of isothermal supersonic turbulence with $M_s = 6$ (Kritsuk et al. 2009). Dissipation-scale structures are shocks with $d_m \approx 2.36$. Inertial-range structures have $d_m \approx 2.3$ (Kritsuk et al. 2007a).}
\end{figure}
turbulence formulated in terms of the velocity alone would depend on the Mach number. At $M_s \lesssim 1$, density fluctuations are relatively small and turbulence remains very similar to the incompressible case with $\zeta_1 \approx 1/3$ (Porter et al. 2002; Benzi et al. 2008). The scaling steepens at higher Mach numbers reaching $\zeta_1 \approx 0.54$ at $M_s \approx 6$ (Kritsuk et al. 2007a; Pan & Scannapieco 2011). This transition is also accompanied by a change in the dimensionality of the most singular dissipative structures from 1 (vortex filaments) to 2 (shocks, Boldyrev 2002; Padoan et al. 2004).

In order to get a universal scaling relation, one would usually have to consider ideal quadratic invariants or, more precisely, rugged invariants. In compressible isothermal flows, however, the situation is more complex. There are two invariants: the mean total energy density $E = \langle \rho u^2 / 2 + c_s^2 \ln (\rho / \rho_0) \rangle$ ($\rho_0$ is the mean density) and the mean helicity. Since $c_s^2 / 2$ is positive semidefinite, its contribution to $E$ dominates at high Mach numbers, while the second term is always subdominant. Hence, in the case of MC turbulence, the kinetic energy density is probably the best possible choice (if any), as far as universality is concerned. In MCs, on scales above the sonic scale, $\ell \gg \ell_s \sim 0.1$ pc turbulence is highly compressible and any quantity with universal scaling must depend on both mass density and velocity.

An illustration is given in Figure 3 where filled circles show the absolute scaling exponents, $\zeta_p$, of the velocity SFs of order $p \in \{0.5, 5.5\}$ at $M_s = 6$. These exponents would be close to the K41 prediction, $\zeta_p = p/3$, at $M_s \lesssim 1$, if we assumed isotropy, homogeneity, and ignored intermittency corrections. At $M_s \gtrsim 3$, $\xi_3$ shows an excess over unity, which systematically increases with the Mach number, indicating a non-universal behavior. A better candidate for universal scaling is the density-weighted velocity, $v = \rho^{1/3} u$ since $\xi_3 \approx 1$ at all Mach numbers (Kritsuk et al. 2007a,b). We will use the third-order moment of $\delta v$ as its linear scaling implies approximately constant kinetic energy flux within the inertial range,

$$S_3(v, \ell) \equiv \langle |\delta u|^3 \rangle = \langle \epsilon \rangle \ell,$$

with some minor intermittency correction (Kritsuk et al. 2007a, 2009). The sonic scale $\ell_s$ is defined by the condition $\delta u_s = c_s$.

Figure 3. Absolute scaling exponents for transverse SFs of velocity ($S_3(v, \ell) \propto \ell^3$, circles) and density-weighted velocity ($\nu = \rho^{1/3} u$ ($S_3(v, \ell) \propto \ell^3$), crosses) from Kritsuk et al. (2007a). Solid lines show $\zeta_p$ predicted by the K41 theory (red), Burgers’ model (blue), and intermittency models due to She & Leveque (1999, green) and Boldyrev (2002, magenta). Note that Burgers’ model predicts $\zeta_1 = 1$ (cf. McKee & Ostriker 2007).

Figure 4. Variation of the scaling coefficient $u_0 = \sigma_3 R^{1/2}$ with mass surface density $\Sigma$ based on data from Heyer et al. (2009). Solid lines with slopes $0.34 \pm 0.04$ and $0.32 \pm 0.03$ show least square fits to A1 and A2 subsets from Heyer et al. (2009), respectively. Dashed line shows the correlation expected for clouds in virial equilibrium.

### 3. Exposing Molecular Cloud Conspiracy

In the following, we exploit the “universal” third-order relation (4) to derive several secondary scaling laws involving $\Sigma$, assuming that the effective kinetic energy flux across the hierarchy of scales is approximately constant within the inertial sub-range (and neglecting gravity).

Dimensionally, the constant spectral energy flux condition,

$$\rho \sigma_0^3 \ell^{-1} \propto \Sigma \ell (\delta u) \ell^{-2} \propto \Sigma \ell^{3/2} \approx \text{const},$$

implies

$$\Sigma \propto \ell^{-3/2} \delta u.$$  

Substituting $\zeta_1 = 0.56 \pm 0.02$, as measured by Heyer & Brunt (2004), we get $\Sigma \propto \rho^{0.32 \pm 0.06}$. We can also rely on the fractal properties of the density distribution to evaluate the scaling of $\Sigma$ with $\ell$: $\Sigma \propto \rho \ell \propto m_\ell / \ell^2 \propto \ell^d - 2$, which in turn implies $\Sigma_\ell \propto \rho^{0.36 \pm 0.04}$ for $d_m = 2.36 \pm 0.04$ from Roman-Duval et al. (2010). Note that both independent estimates for the scaling of $\Sigma_\ell$ with $\ell$ agree with each other within one sigma. New observational data, thus, indicate that mass surface density of MCs indeed positively correlates with their size with a scaling exponent $\approx 1/3$. This result is consistent with both observed velocity scaling and observed self-similar structure of the mass distribution in MCs.

Let us now examine data sets A1 and A2 presented in Heyer et al. (2009) for a possible correlation of $u_0 = \sigma_3 R^{1/2}$ with $\Sigma = m / \pi R^2$. Figure 4 shows formal least-square fits for the two data sets with slopes $0.34 \pm 0.04$ and $0.32 \pm 0.03$, respectively. Note that both correlations are not as steep as the virial equilibrium condition (1) would imply. When the two data sets are plotted together, however, the apparent shift between A1 and A2 points (caused by different cloud boundary definitions in A1 and A2) creates an impression of virial equilibrium condition (dashed line in Fig. 4) being satisfied, although with an offset that Heyer et al. (2009) interpret as a...
consequence of LTE-based cloud mass underestimating real masses of the sampled clouds. Each of the two data sets, however, suggest scaling with a slope around 1/3 with larger clouds of higher mass surface density being closer to virial equilibrium than smaller structures. The same tendency can be traced in the Bolatto et al. (2008) sample of extragalactic GMCs (Hayer et al. 2009, Fig. 8). A similar trend is recovered by Goodman et al. (2009) in the L1448 cloud, where a fraction of self-gravitating material obtained from dendrogram analysis shows a clear dependence on scale. While most of the emission from the L1448 region is contained in large-scale bound structures, only a few fraction of small-scale objects appear self-gravitating.

Let us check a different hypothesis, namely whether the observed scaling $\sigma_n R^{1/2} \propto \Sigma^{1/3}$ is compatible with the turbulent cascade phenomenology and with the observed fractal structure of MCs. The constant spectral energy flux condition, $\rho(\delta u)^2 \ell^{-1} \approx \mathrm{const}$, can be recast in terms of $\Sigma^\ell \propto \rho \ell^3$ assuming $\delta u \ell^{-1/2} \propto \Sigma^\ell$ with $\alpha \approx 1/3$ and $\rho \ell^3 \propto \ell^{-3}$. This condition then simply reads as $2(d_m - 3) + 3/2 \approx 0$ or $d_m \approx 2.25$, which is close to the observed fractal dimension of MCs.

As we have shown above, the observed correlation of the scaling coefficient $\rho_0'$ with the coarse-grained mass surface density of MCs is consistent with a purely turbulent nature of their hierarchical structure and does not require any additional assumptions concerning virial equilibrium. The origin of this correlation is rooted in highly compressible nature of the turbulence that implies density dependence of the lhs of equation (4). Let us rewrite (4) for the first-order SF of the density fluctuation: $(\delta \Sigma / \Sigma) \sim (\ell^{1/3} / \ell^{1/3})$. Due to intermittency, the mean cubic root of the dissipation rate is weakly scale-dependent, $(\ell^{1/3} / \ell^{1/3}) \propto \ell^{1/3}$, and thus $(\delta \Sigma / \Sigma) \propto \ell^{1/3}$, where $\xi_1 = 1/3 + \tau_1/3$ and $\tau_1/3$ is the intermittency correction for the dissipation rate. Using dimensional arguments, one can express the scaling coefficient in the Hayer et al. (2009) relation, $\delta u \ell^{-1/2} \propto \rho_0' \ell^{1/3} / \Sigma^{1/3} \propto \Sigma^{-1/3}$, consistent with the Hayer et al. (2009) data.

### 4. A PLACE FOR GRAVITY

So far, we limited the discussion of Larson’s linewidth−size and mass−size relations to scales above the sonic scale $\ell_s \sim 0.1 \text{ pc}$. Theoretically, the linewidth−size scaling index is expected to approach $\zeta_1 \approx 1/3$ at $\ell \gtrsim \ell_s$ in MC sub−structures not affected by self−gravity (see §2 and Kritsuk et al. 2007a). Falgarone et al. (2009) explored the linewidth−size relation using a large sample of $^{12}$CO structures with $\ell \in [10^3, 10^5] \text{ pc}$. These data approximately follow a power law $\delta u \ell \propto \ell^{1/2}$ for $\ell \gtrsim 1 \text{ pc}$. Although the scatter substantially increases below 1 pc, a slope of 1/3 is “not inconsistent with the data.” $^{12}$CO and $^{13}$CO observations of translucent clouds indicate that small-scale structures down to a few hundred AU are possibly intrinsically linked to the formation process of MCs (Falgarone et al. 1998; Heithausen 2004).

The observed mass−size scaling index, $d_m \approx 2.36$, is expected to remain constant for non-self−gravitating structures down to $\ell_s \sim 30 \ell_s$, which is about a few hundred AU, assuming the Kolmogorov scale $\eta \sim 10^{14} \text{ cm}$ (Kritsuk et al. 2011). This trend is traced down to $\sim 0.01 \text{ pc}$ with recent Herschel detection of $\sim 300$ unbound starless cores in the Polaris Flare region (André et al. 2010). For scales below $\ell_s \sim 200 \text{ AU}$, in the turbulence dissipation range, numerical experiments predict convergence to $d_m \approx 2$ due to shocks, see Fig. 2.

In star−forming clouds, the presence of strongly self−gravitating clumps of high mass surface density breaks self−similarity imposed by turbulence. One observational signature of gravity is the build−up of a high−end power−law tail in the column density PDF associated with filamentary structures harboring prestellar cores and YSOs (Kainulainen et al. 2009; André et al. 2011). The power index of the tail, $p = 2 - 1/(n - 1)$, is determined by the density profile, $\rho \propto r^{-n}$, of a stable attractive self−similar collapse solution appropriate to the specific conditions in the turbulent cloud (Kritsuk et al. 2011a). In numerical simulations with self−gravity, we independently measured $p \approx 2.5$ and $n \approx 1.8$ in agreement with the theoretical prediction. This implies $d_m = 3 - n \approx 1.2$ for the mass−size relation on scales below $\sim 0.1 \text{ pc}$. Mapping of the active star−forming Aquila field with Herschel gave $p = 2.7 \pm 0.1$ and $d_m = 1.13 \pm 0.07$ for a sample of 541 starless cores with deconvolved FWHM size $\ell \in [0.01, 0.1] \text{ pc}$ (König et al. 2010; André et al. 2011). Using the above formalism, we get $d_m = 3 - n = 2 + 2/2 \approx 1.26$ in reasonable agreement with the direct measurement. Overall, the expected mass dimension at scales where self−gravity becomes dominant should fall between $d_m = 1$ (Larson−Penston solution, $n = 2$) and $d_m = 9/7 \approx 1.29$ (pressure−free collapse solution), see Kritsuk et al. (2011a).

The characteristic scale where gravity takes control over turbulence can be predicted using the linewidth−size and mass−size relations discussed in previous §§. Indeed, in a turbulent isothermal gas, the coarse−grained Jeans mass is a function of scale $\ell$ $m_\ell = \propto \rho_0' \ell^{1/2} \propto \rho_0' \ell^{1/3} / \Sigma^{1/3}$, (8)

Since, as we have shown above, $\Sigma \propto \ell^{1/3}$, one gets $\delta u \ell^{-1/2} \propto \rho_0' \ell^{1/3} / \Sigma^{1/3} \propto \Sigma^{-1/3}$. This value implies scaling, $\delta u \ell^{-1/2} \propto \Sigma^{0.33}$, consistent with the Hayer et al. (2009) data.
thus, sets the characteristic mass of the core mass function, $m_{\ell_c}$, and the threshold mass surface density for star formation, $\Sigma_{\ell_c}$ (cf. Krumholz & McKee 2005; André et al. 2010).

5. CONCLUSIONS AND FINAL REMARKS

We have shown that, with current observational data for large samples of Galactic MCs, a modern version of Larson’s relations on scales 0.1 – 50 pc can be interpreted as an empirical signature of supersonic turbulence fed by the large-scale kinetic energy injection. Our interpretation is based on the phenomenology of highly compressible turbulence and supported by high-resolution numerical simulations.

Gravity cannot nevertheless help accumulate the largest molecular structures ( $\gtrsim$ 50 pc) that appear gravitationally bound. High-resolution simulations of cloud formation in the general ionized/atomic/molecular turbulent ISM context are needed to demonstrate that molecular structures identified as bound in position-position-velocity space are indeed genuine three-dimensional objects. On small scales, in low-density translucent clouds, self-similarity of turbulence can be preserved down to $\sim 10^{-3}$ pc, where dissipation starts to become important. In contrast, in overdense regions, the formation of prestellar cores breaks the turbulence-induced scaling and self-gravity assumes control over the slope of the mass–size relation. We show that the transition from turbulence- to gravity-dominated regime in this case occurs close the sonic scale $\ell_s \sim 0.1$ pc, where structures turn gravitationally unstable first, leading to the formation of prestellar cores.

Our approach is essentially based on dimensional analysis and the results are valid in a statistical sense. This means that the scaling relations we discuss hold for averages taken over a large number of statistically independent realizations of a turbulent flow. Relations obtained for individual MCs and their internal substructure can show substantial statistical variations around the mean. The scaling exponents we discuss or derive are usually accurate within $\approx (5 - 10)\%$, while scaling coefficients bear substantial systematic errors. Homogeneous multiscale sampling of a large number of MCs and their internal structure (including both kinematics and column density mapping) with CCAT, SOFIA and ALMA will help to detail the emerging picture discussed above.

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