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The linewidth-size scaling law of molecular gas revisited

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Abstract. The origin of the linewidth-size (LWS) scaling law, first noticed by Larson three decades ago and ascribed to turbulence, is still a highly debated issue. Not unexpectedly, its properties depend on the environment and on the line tracer used. When the optically thick ^{12}CO (J=1-0) line is used, a specific medium is sampled: the translucent molecular gas of moderate density that builds up the bulk of the molecular interstellar medium in galaxies like the Milky Way. The sensitivity of the ^{12}CO line to this gas is such that the LWS is found to hold over almost five orders of magnitude in lengthscale, although with a considerable scatter (± 0.5 dex). It also appears to split into two regimes, depending on the gas mass surface density: below a given threshold that is proposed to be linked to the galactic structure, it bears the signature of a turbulent cascade, while above it, the scaling law is ascribed to virial balance. Large deviations from the LWS scaling law are observed at small scales where signatures of turbulent intermittency appear. The mass-size scaling law built with the ^{12}CO (J=1-0) line also splits into two regimes. The mass surface density is uniform (also with a large scatter) above lengthscales $\sim$ 10pc and increases with size at smaller scales, following turbulence predictions. The two thresholds define an average gas density $\overline{n}_{\rm H} \sim 300$ cm^{-3}.

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The controversy on the origin of the scaling laws that rule the internal velocity dispersion σ_v, the mass surface density Σ, the radius R (or sizescale l) and therefore the mass M of molecular clouds bears on the respective roles of turbulence and gravity. By using the optically thick ^{12}CO line, measurements are extended to column densities one order of magnitude smaller than those sampled with the ^{13}CO(1-0) line (Heyer *et al.* 2009). The CO-bright structures of lowest column density (called "molecular sites" rather than "molecular clouds", see Hennebelle & Falgarone 2012) build up the mass of the giant molecular clouds (GMC).

Theoretical predictions are as follows. The predicted scalings are so distinct, whether the dynamics is regulated by gravity or turbulence, that confrontation with observations should be conclusive : (i) A critical hierarchy of self-gravitating polytropes embedded in an external pressure is determined only by the value of this external pressure. Then the scaling laws write: $\sigma_v/\sqrt{R} \propto P_{ext}^{1/4}$ and $M/R^2 \propto P_{ext}^{1/2}$ (Chièze 1987, Field *et al.* 2011). (ii) In compressible turbulence where the kinetic energy transfer rate ϵ is the invariant of the cascade, $\epsilon = \rho\sigma_v^3/l$ (Hopkins 2012, Kritsuk *et al.* 2013), then $\Sigma \propto \epsilon l^{1/2}$. (iii) For isolated structures in virial balance between internal kinetic energy and self-gravity, $5\sigma_v^2/R = G\Sigma$ hence $\sigma_v/\sqrt{R} \propto \Sigma^{1/2}$.

For a broad sample of structures detected in the ^{12}CO line, from small scale molecular sites (Falgarone *et al.* 2009) to Super GMCs detected in the interaction region of the

Antennae galaxies (Wilson *et al.* 2000), the LWS $\sigma_v \propto l^{1/2}$ and the mass-size $M \propto l^2$ scaling laws extend from 0.01 pc to 1 kpc. However, the physics of interest lies in the departure from these scaling laws. The $\sigma_v/\sqrt{l}$ plot as a function of Σ defines two regimes, see McKee *et al.* (2010): below $\Sigma_{cr} \approx 100\mathrm{M}_\odot$ pc^{-2}, $\sigma_v/\sqrt{l} \sim$ cste down to $\Sigma \sim 1\mathrm{M}_\odot$ pc^{-2} (or $N_\mathrm{H} \sim 10^{20}$ cm^{-2}), therefore over two orders of magnitude of the mass surface density. Above that threshold, $\sigma_v/\sqrt{l}$ approximately increases as $\Sigma^{1/2}$ as predicted for clouds in virial equilibrium. Yet, as already discussed by Field *et al.* (2011), the data points lie above the $\Sigma^{1/2}$ slope corresponding to isolated clouds. The departure is larger for the largest surface densities. This is so because GMCs are not isolated but are bounded by a high external pressure that results from the equilibrium of the external medium in the large scale gravity field (Chièze 1987, Elmegreen 1989, Field *et al.* 2011). For GMCs, it may involve the disk gravitational pressure $P_G = G\Sigma^2_{\mathrm{star+DM}}$ where the average stellar and dark matter (DM) surface density increases exponentially towards the galactic center (Bovy & Rix 2013).

Interestingly, the mass-size scaling law can be analyzed in a similar way over the five orders of magnitude in sizescale provided by the ^{12}CO data : $\Sigma \propto M/R^2$ traces the departure from the average value. Above a sizescale of ~ 10 pc, Σ is found to be constant up to the Super GMCs sizescale (1 kpc), although with a large scatter by a factor 5 to 10 due to the variations of confining gravitational pressures discussed above. Below this sizescale, $\Sigma \propto R^{1/2}$ over about three orders of magnitude in scale. This is the scaling $\Sigma \propto \epsilon l^{1/2}$ predicted by compressible turbulence. Here, again, the two same regimes are separated by a critical sizescale. The scatter of the data points in each regime is large but the range of accessible sizescales provided by the ^{12}CO data is such that these trends are clearly identified for the first time.

Last, the critical mass surface density $\Sigma_{cr} \sim 100\mathrm{M}_\odot$ pc^{-2} revealed by the behavior of $\sigma_v/R^{1/2}$ and the critical lengthscale $l_{cr} \sim 10$ pc inferred from that of M/R^2 may be turned into a critical *average* density, $n_{cr} \propto \Sigma_{cr}/l_{cr} \sim 300$ cm^{-3}, that separates compressible turbulence from self-gravitating virialized entities. It is remarkable that this density is the same as that where the magnetic field intensity begins to change with density (Crutcher *et al.* 2010). In this study, the critical density is also interpreted as that at which self-gravity starts modifying the behavior of magnetic field with density.

In summary, we find that among all the scales that follow the LWS and mass-size scaling laws, built on ^{12}CO lines, from small scale molecular sites to super GMCs, two regimes coexist : diffuse gas ruled by compressible turbulence and large and more massive virialized entities. This study does not include dense molecular cores and star forming regions. This is part of an upcoming paper.

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