Not to appear in Nonlearned J., 45.

Turbulence in molecular clouds - discussion, Aspen 06/10/2019

Stefanie Walch[1]

walch@ph1.uni-koeln.de

Norman Murray [2]

ABSTRACT

We aim to discuss turbulence in molecular clouds (GMC = giant molecular cloud). We first introduce the relevant properties of GMCs. Then we continue to discuss the possible turbulence drivers for highly turbulent and moderately turbulent clouds. We also quickly go into turbulence decay, but actually do not pay too much attention to it because clouds seem to be short-lived, so there might be no need to sustain turbulence. We finish presenting our view on turbulence in GMCs based on the essence of the observational results obtained up to today.

Currently there are two main competing models to explain the turbulence within GMCs:

1. Fully developed turbulence driven on large (100 pc) scales by some process (e.g. Federrath et al. 2008; Padoan & Nordlund 2011)
2. Global gravitational collapse (Ballesteros-Paredes et al. 2011; Vázquez-Semadeni et al. 2019), probably also Murray (2011).
3. Something in between, which had been put forward by (e.g. Murray & Chang 2015)

Subject headings: Turbulence in GMCs

[1]I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Cologne, Germany

[2]Canadian Institute for Theoretical Astrophysics, 60 St. George Street, University of Toronto, Toronto ON M5S 3H8, Canada

1. GMC properties

Here we discuss the GMC properties which led to the understanding that GMCs are subject to supersonic turbulence.

1.1. Steffi

1. CO detections in the 70's (there is a comprehensive list in Larson, 1981). Clouds are filamentary and/or clumpy, i.e. irregular, and have structure on all resolvable scales.

2. Linewidths ($\sim$ 0.2 km/s – 6 km/s) are much larger than thermal ($T = 10$ K leads to $c_s = 0.2$ km/s).

3. Correlation of $L_{\rm CO} \propto M_{\rm GMC}$ was found.

4. Cloud surface densities $\Sigma_{\rm gas} \sim 3 - 100$ M$_\odot$ pc^{-2}. People realized quickly (e.g. Phillips et al. 1979, by comparing different molecular line tracers) that $\tau_{12CO} >> 1$ in typical GMCs, because CO needs $A_V \sim 1$ to form and becomes optically thick at $A_V \gtrsim 3$. So in that case only the surface of the clouds would be visible and the correlation between $L_{\rm CO}$ and $M_{\rm GMC}$ could not be explained. Somehow CO seems to be tracing the whole cloud after all.

5. The way to do it is to have a large velocity gradient across the cloud (such that line center is shifting continuously, making the whole cloud visible in CO). Goldreich & Kwan (1974) suggest that gravitational collapse would cause such a velocity gradient.

6. But if all GMCs were collapsing, the star formation rate $\dot{M}_\star$ would be $\sim$100 times too large (Zuckerman & Palmer 1974).

7. Then Larson (1981) measured the correlation of linewidth and linear, projected size of the GMC. The telling signature to distinguish between turbulence and gravitational collapse could be the relative magnitude of small-scale and large-scale motions, i.e the spectrum. Turbulence would also form the density variations seen in GMCs (although gravity can do the same).

8. Filamentary substructure can be caused by gravity and/or turbulence.

9. In the 70's it was unclear if the internal kinematics is better explained by collapse, rotation, small-scale random motion or random motion of sub-structures - As we show later it is still unclear, but we are getting there...

10. Surface density PDFs for GMCs are lognormal, e.g., Lombardi et al. (2006), consistent with supersonic turbulence.

11. On the scale of clumps, surface density PDFs show power-law tails to high density Kainulainen et al. (2009).

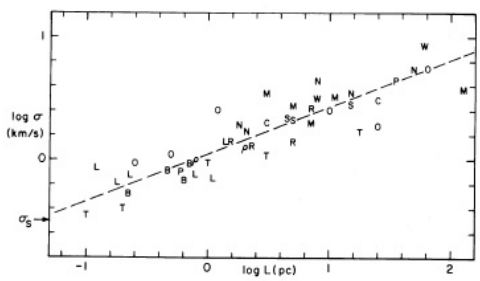

Figure 1. The three-dimensional internal velocity dispersion σ plotted versus the maximum linear dimension L of molecular clouds and condensations, based on data from Table 1; the symbols are identified in Table 1. The dashed line represents equation (1), and σ_s is the thermal velocity dispersion.

1.2. Norm

1. What physics give rise to Larson's law? For example, virial equilibrium or turbulence? If GMCs are in virial equlibrium, $\alpha_{\rm vir} = 5\frac{\sigma^2 R}{GM} = 1$ gives $\sigma \propto R^{-1/2}$. On the other hand, turbulence will give similar scaling relations independent of gravity, e.g., Kolmogorov type arguments, assuming that motions created at large scales will suffer from instabilities (if the Reynolds number is large enough), driving smaller scale motions. If the stirring lasts for several eddy turnover times (v_T/L, where L is the driving scale, the kinetic luminosity $L_{\rm kin} = \rho v_T(l)^2 \cdot v_T(l)/l = const.$ gives $v_T(l) \propto l^{-1/3}$, where ρ is taken to be constant, valid for subsonic turbulence. Simulations of supersonic turbulence show $v_T(l) \sim l^{1/2}$.

2. GMC lifetimes: Early estimates, e.g., (Scoville & Hersh 1979) suggested that GMCs lasted 10^8 yrs.

3. How to keep the cloud from collapsing? Stabilisation by magnetic fields was proposed (Mouschovias)

4. However observations of cloud magnetic field strengths using Zeeman splitting (Crutcher) showed that clouds are supercritical.

5. Can turbulence sustain collapse? Turbulent pressure $P_{\rm turb} = \rho\sigma^2$ gives an OOM estimate, however we should really interpret this like a Reynolds stress ρv_T^2. In principle no magnetic field needed.

6. More recent estimates of molecular cloud lifetimes from populations statistics (Number of GMCs with/without star formation and (nowadays) number of young clusters to estimate dispersal time scale) confirms short lifetimes of only 2-3 freefall times (equals crossing times on these scales) (Blitz & Shu 1980; Fukui et al. 1999; Hartmann et al. 2001; Murray 2011; Kruijssen et al. 2019). Plot by Schruba showing the "scissors" (Schruba et al. 2010).

2. Where does MC turbulence come from and where does it go?

2.1. Norm

1. Plot of $\alpha_{\rm vir}$ vs. $M_{\rm GMC}$ shows high $\alpha_{\rm vir}$ for many clumps (see Fig.1 and Fig.2 left).
   - Giannetti et al. (2013) uses IRAS sources
   - Also Kauffmann et al. (2013) find $\alpha_{\rm vir} \propto\propto M^{-1...-0.4}$.
   - Urquhart et al. (2018) use ATLAS-Gal to determine $\alpha_{\rm vir} \propto M^{-0.5}$.
   - Traficante et al. (2018) uses 213 Herschel Hi-Gal sources and find no agreement with Larson.

2. GMC linewidth as a function of Galactocentric radius in disk: increase towards center.

2.2. Steffi

1. (Goldreich & Kwan 1974) already argued that turbulent motions would be quickly damped and could not hinder gravitational collapse. Stone et al. (1998) and Mac Low et al. (1998) showed numerically, that the decay time scale of supersonic turbulence in magnetized, isothermal gas is of the order of a crossing time: $\tau_{\rm decay} \sim L/v_T$.

2. Decay could be driven by a cascade a la Kolmogorov: $v \sim l^{1/3}$ (subsonic)

3. Decay could be driven by shocks (Burgers turbulence): $v \sim l^{1/2}$ (supersonic)

4. Solenoidal and compressively driven turbulence decays in a similar manner because a thermal mix of modes is supposedly developed quickly in a cascade: equipartition leads to 2:1 ratio of solenoidal ($\vec{\nabla} \times \vec{v}$) and compressive ($\vec{\nabla} \cdot \vec{v}$) modes.

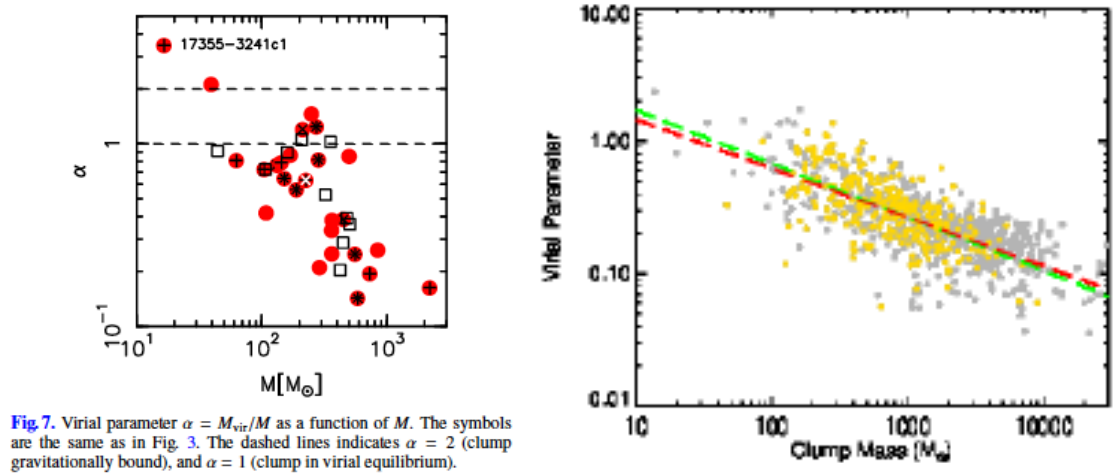

Fig. 1.— Left: IRAS colour-selected sources from Giannetti et al. (2013). Rigth: ATLAS-Gal sources from Urquhart et al. (2018).

2.3. Norm

1. Possible turbulence drivers for high-$\alpha_{\rm vir}$ clouds: these are certainly not driven by global gravitational collapse.
    - Stellar feedback (from outside) e.g., Vishniac 1994
    - Gravitational instabilities in the galactic disk; accretion through the disk
    - Galactic gravitational potential (recent work by Meidt et al. 2018)
    - Shear
    - Accretion from the halo
    - Mergers
    - MRI (outer disk; Balbus)
    - Thermal instability?
2. Drivers for low-$\alpha_{\rm vir}$ clouds:
    - all of the above processes
    - self-gravity: contraction or catastrophic collapse
    - typically star formation inside: feedback

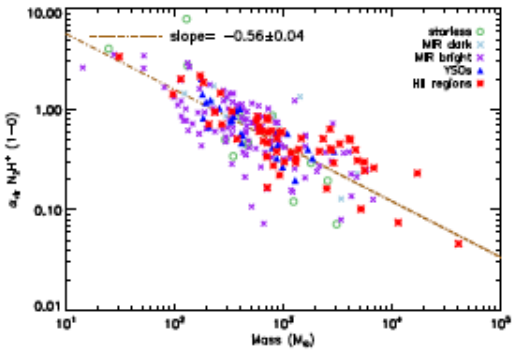

Figure 9. Virial parameter distribution as function of mass. The red dashed line is the best-fit to our data, which gives a slope $\alpha = -0.56 \pm 0.04$.

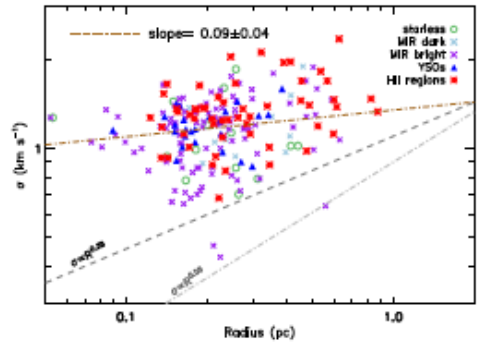

Figure 4. First Larson relation: velocity dispersion σ as function of the radius R. The dark grey dashed line is the original Larson's relation, $\sigma \propto R^{0.38}$, the light grey dash-dotted line is the revised Heyer & Brunt (2004) relation, $\sigma \propto R^{0.56}$. The correlation is weak, with a Pearson's coefficient of $\rho = 0.26$.

Fig. 2.— Left: Herschel Hi-Gal sources from Traficante et al. (2018). Right: Larson relation for massive clumps in Traficante et al. (2018). As expected for sources which are dominated by gravitational collapse, the powerlaw is much flatter than $\sigma \propto R^{-1/2}$. They rather find $\sigma \propto R^{-1/10}$.

3. Latest observational evidence shows deviations from Larson's law for massive, starless clumps $\sim 10^2 - 10^4$ $M_\odot$: $\sigma \propto l^{-||p||}$ with flatter $p < 1/3$ (see Fig. 2, right panel). This is evidence for driving by gravitational collapse! (Williams et al. 2018), Plume, Contreras papers. However these clumps don't dominate the large-scale σ of the cloud because they make up just $\sim 1\%$ of the mass.

4. Inverse P-Cygni profiles are also observed towards such clumps: further evidence for infall

3. Opinions

3.1. Steffi

1. There is turbulence in GMCs, although not necessarily fully developed turbulence.

2. Turbulence does not support low-$\alpha_{\rm vir}$ clouds (collapse), neither does it support high-$\alpha_{\rm vir}$ clouds (disperse). But it also doesn't need to because cloud lifetimes are short.

3. So what is the fate of a low-$\alpha_{\rm vir}$ cloud?

4. Turbulence from diffuse medium can basically not be transported into the dense gas (Seifried 2018 for SNe pushing on a cloud from the outside).
5. Gravity-driven turbulence on clump scales: 0.01 - 1 pc
6. This is associated with star formation
7. Stellar feedback follows and first cuts off the local fuel supply
8. The feedback disrupts the GMC.

3.2. Norm

Comparison of turbulent driving energies. Luminosity in turbulent motions is

$$L_{\rm turb} = \frac{1}{2} M_{\rm gas} v_T^2 \frac{v_T}{H} = \frac{1}{2} M_{\rm gas} v_T^2 \frac{v_c}{R} \sim 10^{40}\ \frac{\rm erg}{\rm s} \tag{1}$$

Here R is the galactocentric radius (later on set to few kpc), $v_c \sim 200$ km/s is the rotation velocity in the disk, $v_T \sim 10$ km/s is the turbulent velocity, $M_{\rm gas} \sim 5 \times 10^9$ $\mathrm{M}_\odot$ is the gas mass in the disk.

(1) Turbulence driven by accretion through the disk

$$L_{\rm acc} = \frac{GM\dot{M}_\star}{R} = v_c^2 \dot{M}_\star \tag{2}$$

Ratio of the two:

$$\frac{L_{\rm acc}}{L_{\rm turb}} = 2\frac{v_c^2 \dot{M}_\star}{M_{\rm gas} v_T^2 \frac{v_c}{R}} = 2\frac{v_c \dot{M}_\star}{M_{\rm gas} v_T^2} R = 2\frac{v_c}{v_T}\frac{\dot{M}_\star}{M_{\rm gas}}\frac{R}{v_T} \approx 1 \tag{3}$$

Here we used $\dot{M}_\star = 1 \frac{\mathrm{M}_\odot}{\rm yr}$ for the Milky Way and $R = 3$ kpc.

(2) Supernova luminosity (note that we neglect energy losses here!):

$$L_{\rm SN} = \epsilon_{SN} \dot{M}_\star c^2. \tag{4}$$

What is ϵ_{SN}? We estimate 1 SN / 100 solar masses of stars, so for $\dot{M}_\star = 1 \frac{\mathrm{M}_\odot}{\rm yr}$ we get 10^{-2} SN/yr. Each SN deposits $E_{\rm SN} = 10^{51}$ erg, so we get 10^{49} erg/yr, which is about 3×10^{41} erg/s.

On the other hand we have[1] $\dot{M}_\star c^2 = 6.3 \times 10^{25}$g/s $\times\ 9 \times 10^{20}$cm/s $= 5.7 \times 10^{46}$ erg/s.

[1] $1 \frac{\mathrm{M}_\odot}{\rm yr} = 6.3 \times 10^{25} g/s$

So this gives $\epsilon_{SN} = \frac{3\times10^{41}}{5.7\times10^{46}} = 5.3 \times 10^{-6}$.

Now comparing these two luminosities gives

$$\frac{L_{\rm SN}}{L_{\rm turb}} = \frac{\epsilon_{SN}\dot{M}_\star c^2}{M_{\rm gas} v_T^2 \frac{v_c}{R}} = \frac{3\times10^{41}}{10^{40}} \sim 30. \tag{5}$$

Given that about 90% of the SN energy is dissipated, we have a similar amount of energy input by SNe compared to accretion through the disk. In addition we have other sources of energy, like radiative feedback from stars, infall, etc. So it seems that we actually have way too much energy available. In particular, it seems that we have to get rid of a large fraction of the SN energy by other means than radiative losses.

So our opinion is that Supernovae

- Create a hot volume filling phase (e.g. bubbles and super bubbles)
- By these means sweep up some of the surrounding gas
- But also are quite efficient in venting gas out of the disk midplane (onset of galactic fountains and winds) (see Gatto et al. 2017, for showing that a VFF of hot gas of more than 50% leads to outflow)
- Probably are necessary to quench star formation in massive GMCs, where HII regions and winds alone are insufficient.

This is very different from the model of self-regulated star formation.

The ultimate goal would be to determine what process is the main turbulence driver (possibly as a function of galactic environment). What would be interesting is to measure the infall rate vs. the accretion rate through the disk.

4. Conclusions

REFERENCES

Ballesteros-Paredes, J., Hartmann, L. W., Vázquez-Semadeni, E., Heitsch, F., & Zamora-Avilés, M. A. 2011, MNRAS, 411, 65

Fig. 3.— bla

Blitz, L. & Shu, F. H. 1980, ApJ, 238, 148

Federrath, C., Klessen, R. S., & Schmidt, W. 2008, ApJ, 688, L79

Fukui, Y., Mizuno, N., Yamaguchi, R., Mizuno, A., Onishi, T., Ogawa, H., Yonekura, Y., Kawamura, A., Tachihara, K., & Xiao, K. 1999, PASJ, 51, 745

Gatto, A., Walch, S., Naab, T., Girichidis, P., Wünsch, R., Glover, S. C. O., Klessen, R. S., Clark, P. C., Peters, T., Derigs, D., Baczynski, C., & Puls, J. 2017, MNRAS, 466, 1903

Giannetti, A., Brand, J., Sánchez-Monge, Á., Fontani, F., Cesaroni, R., Beltrán, M. T., Molinari, S., Dodson, R., & Rioja, M. J. 2013, A&A, 556, A16

Goldreich, P. & Kwan, J. 1974, ApJ, 189, 441

Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. A. 2001, ApJ, 562, 852

Kainulainen, J., Beuther, H., Henning, T., & Plume, R. 2009, A&A, 508, L35

Kauffmann, J., Pillai, T., & Goldsmith, P. F. 2013, ApJ, 779, 185

Kruijssen, J. M. D., Schruba, A., Chevance, M., Longmore, S. N., Hygate, A. e. P. S., Haydon, D. T., McLeod, A. F., Dalcanton, J. J., Tacconi, L. J., & van Dishoeck, E. F. 2019, Nature, 569, 519

Larson, R. B. 1981, MNRAS, 194, 809

Lombardi, M., Alves, J., & Lada, C. J. 2006, A&A, 454, 781

Mac Low, M.-M., Klessen, R. S., Burkert, A., & Smith, M. D. 1998, Physical Review Letters, 80, 2754

Meidt, S. E., Leroy, A. K., Rosolowsky, E., Kruijssen, J. M. D., Schinnerer, E., Schruba, A., Pety, J., Blanc, G., Bigiel, F., & Chevance, M. 2018, ApJ, 854, 100

Murray, N. 2011, ApJ, 729, 133

Murray, N. & Chang, P. 2015, ApJ, 804, 44

Padoan, P. & Nordlund, Å. 2011, ApJ, 730, 40

Fig. 4.— bla

Phillips, T. G., Huggins, P. J., Wannier, P. G., & Scoville, N. Z. 1979, ApJ, 231, 720

Schruba, A., Leroy, A. K., Walter, F., Sand strom, K., & Rosolowsky, E. 2010, ApJ, 722, 1699

Scoville, N. Z. & Hersh, K. 1979, ApJ, 229, 578

Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, ApJ, 508, L99

Traficante, A., Duarte-Cabral, A., Elia, D., Fuller, G. A., Merello, M., Molinari, S., Peretto, N., Schisano, E., & Di Giorgio, A. 2018, MNRAS, 477, 2220

Urquhart, J. S., König, C., Giannetti, A., Leurini, S., Moore, T. J. T., Eden, D. J., Pillai, T., Thompson, M. A., Braiding, C., & Burton, M. G. 2018, MNRAS, 473, 1059

Vázquez-Semadeni, E., Palau, A., Ballesteros-Paredes, J., Gómez, G. C., & Zamora-Avilés, M. 2019, arXiv e-prints

Williams, G. M., Peretto, N., Avison, A., Duarte-Cabral, A., & Fuller, G. A. 2018, A&A, 613, A11

Zuckerman, B. & Palmer, P. 1974, ARA&A, 12, 279