Structure formation and scaling relations in the ISM (large scale)

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February 2017
Eine Methode zur Untersuchung der Turbulenz der interstellaren Materie.

Von
SEBASTIAN VON HOERNER in Göttingen.

Mit 10 Textabbildungen.

(Eingegangen am 16. Juni 1951.)

Die Statistik der Punktpaare zeigt, daß ein Spektrum der Turbulenz im Orionnebel ohne Zweifel vorhanden ist. Der Exponent $a$ des Spektralgesetzes ($u = C \Lambda^a$ für $\Lambda \gg R$) liegt in:

$$1/4 \leq a \leq 1/2$$

Gas velocity difference vs. position difference in Orion Nebula
Miville-Deschenes +17: 8107 clouds from the Dame +01 Milky Way survey using Gaussian fits to the spectra and hierarchical merging.

Su +16: outer MW molecular clouds on far side (l=35-45); circle size = luminosity, <distance> = 15 kpc so 10 pc = 2.29’

Rice +16: Dame survey CO clouds identified with dendograms.
Blue = near distance, inner disk
Red = far distance, inner disk
Black = outer disk
Kauffmann +16: N$_2$H$^+$ and dust clouds in the central molecular zone. (Orbits from Kruijssen +15).

$\sigma$-R relation of the CMZ (blue) compared to N$_2$H$^+$ in the plane (dark green), CO in the plane (light green), N$_2$H$^+$ in the CMZ from Shetty +12 (black box).

CMZ $\sigma(R)$ is higher than in the plane by x10
Faesi +16: NGC 300
(circles = SMA & APEX beams. Gray = Spitzer MIPS 24 μm.)

Kepley+16: II Zw 40 (red), a starburst dwarf.
The position of the identified clouds and their virial parameter,
\( M_{13\text{CO}} / M_{\text{vir}} \), superposed on the pseudo-
\( 13\text{CO}(J=1–0) \) integrated intensity image. The size of circles is proportional to virial parameter of each cloud (from 0.04 to 3.9), and the color of circles indicates their boundness; magenta and green circles are GMCs with virial parameter larger than 1 (i.e., supercritical) and smaller than 1 (subcritical), respectively.

The correlation between molecular gas mass (LTE mass) and virial mass of the identified GMCs based on the \( 13\text{CO}(J=1–0) \) in NGC 1068, together with molecular cores/clumps in W51 (Parsons et al. 2012, \( 13\text{CO}(J=3–2) \)); note that the data points are quantized due to the original data), and GMCs/GMAs in local galaxies including LMC (Fukui et al. 2008, \( 12\text{CO}(J=1–0) \)), M33 (Onodera et al. 2012, \( 12\text{CO}(J=1–0) \)), M51 (Colombo et al. 2014, \( 12\text{CO}(J=1–0) \)) and M83 (Muraoka et al. 2009, \( 12\text{CO}(J=3–2) \)). The diagonal line shows \( M_{\text{LTE}} = M_{\text{vir}} \).

Tosaki +14: NGC 1068 (Seyfert galaxy)
Leroy +15: NGC 253 Starburst nucleus with ALMA
Rubio +15: WLM dwarf
CO(1-0)

Schruba +17: NGC 6822 dwarf

→ weight & absorption from overlying HI+H$_2$ layer gives the CO core inside a “normal” pressure and $\sigma(R)$ relation
Hacar +16: Origin of the line profiles:

A superposition of tiny optically-thick pieces which are individually line-broadened.

Also satisfies constraint that the CO(2-1)/CO(1-0) excitation ratio is independent of brightness (Falgarone +98)

Lynds 1517

curves: thermal broadening (10K) with non-thermal components of 0.5, 1, and 1.5 x sound speed.

corrected for opacity, the velocity dispersion is ~0.5-0.9 times the sound speed.
Kritsuk +07: What should we expect from supersonic turbulence?

von Weizsacker ‘51, Fleck ‘96 assume ρ is related to scale L:

\[
\frac{\rho_i}{\rho_{i-1}} = \left( \frac{L_i}{L_{i-1}} \right)^{-3\kappa}
\]

Lighthill ‘55: volume energy transfer rate:

\[
\frac{\rho \sigma^3}{L} = \text{constant}
\]

Then:

\[
\sigma \sim L^{1/3 + \kappa} \quad ; \quad M(L) \sim L^{3-3\kappa} \quad ; \quad P_{KE}(k) \sim k^{-5/3 - 2\kappa}
\]

(from \(\sigma^2/k\))

Setting the interface fractal dimension from Meneveau & Sreenivasan (1990)

\[
D_{\text{interface}} = 2 + \frac{d\sigma}{dL} = 2 + 1/3 + \kappa
\]

equal to the mass fractal dimension \(D_m = (3-3\kappa)\) gives \(\kappa = 1/6\) and \(\sigma \sim L^{0.5}\)
Kritsuk +07 confirm this with a $1024^3$ simulation of isothermal turbulence at Mach 6.

Using the density scaling from the ratio of the KE to the velocity power spectra:

$$\rho \sim \frac{P_{KE}}{P_{vel}} = \frac{k^{-1.52}}{k^{-1.97}} = k^{0.45} = L^{-3\kappa} \quad \Rightarrow \quad \kappa \sim 0.15, \quad \Rightarrow \quad \sigma \sim L^{0.45}$$
With $\kappa \sim 0.16$, $M(L) \sim L^{3-3\kappa}$ implies the slope is 2.5; observe $\sim 2.2$.
What about gravity? From the Virial Theorem:

\[ 2T + \Omega = 4\pi PR^3 \]

\[ 3M\sigma^2 - \frac{3GM^2}{5R} = 4\pi R^3 P \]

\[ \sigma^2 = R \left( 0.2\pi G\Sigma + 1.33P/\Sigma \right) \rightarrow \text{if } P \text{ and } \Sigma \text{ are constant, expect } \sigma \sim R^{0.5} \]

if \( \Sigma \) and \( P \) vary,

\[ \sigma^2 = 0.2\pi GR\Sigma \left( 1 + \frac{6.67P}{\pi G\Sigma^2} \right) \]

With gravity dominant over pressure:

\[ \sigma (\text{km/s}) = 0.05 \left( \frac{R\Sigma}{M_\odot / \text{pc}} \right)^{0.5} (1 + \ldots)^{0.5} \]

e.g., Heyer +09
Miville-Deschenes +17: Milky Way

\[ \sigma_v \sim (\Sigma R)^{0.43} \] (\( \sim 4 \times \) bigger than simple theory)

Leroy +16: many galaxies with 60 pc beam (fixed R) averaged over 500 pc regions. Slopes \( \sim 0.5 \)
If boundary pressure is important, e.g., for diffuse clouds, then include the second term:

$$\sigma(\text{km/s}) = 0.05 \left( \frac{R \Sigma}{M_\odot/\text{pc}} \right)^{0.5} \left( 1 + \frac{6.67 P}{\pi G \Sigma^2} \right)^{0.5}$$

where

$$\frac{2P}{\pi G \Sigma^2} = 0.03 \left( \frac{P}{kT} \right) \left( \frac{\Sigma}{M_\odot/\text{pc}^2} \right)^{-2}$$

is the ratio of boundary pressure to self-gravitational pressure.

e.g., Field, Blackman & Kent 2011
Leroy +15: NGC 253 starburst nucleus with ALMA
The virial parameter contains $\sigma(R)$ and $M(R)$, which from Kritsuk +07, converts to $M^{-0.2}$

\[
\alpha = \frac{5\sigma^2 R}{GM(R)} \propto \frac{R^{2/3+2\kappa}}{R^{3-3\kappa}} \propto M^{-0.2} \quad \text{for } \kappa \sim 1/6
\]

→ part of this $\alpha$ variation is from internal scaling

→ part is from a transition from diffuse to self-gravitating clouds as $M$ increases

\[
\alpha = \frac{2T}{\Omega} = \frac{5\sigma^2 R}{GM} = 1 + \frac{6.67P}{\pi G \Sigma^2}
\]
\( \alpha \) depends on the maximum mass in the survey

\[ M_{\text{MW}} \]

Pipe Nebula

Lada +08

\[ \alpha \sim M^{-0.86} \]

Planck dust clumps

Zhang +16

\[ \alpha = 16.34 M^{-0.74}, R^2 = 0.746 \]
Most of the mass in a survey is from a few gravitating clouds near the largest mass. But there are always a large number of smaller diffuse clouds at high $\alpha$ and smaller self-gravitating clouds at low $\alpha$. 

The graph shows a scatter plot with a slope of approximately -0.5. The x-axis represents mass $M$ in units of $M_{\text{Sun}}$, and the y-axis represents another variable, possibly mass density or another relevant quantity. The lines indicate regions of interest such as Planck clumps (outer MW), Pipe Nebula, and Cha III.
Cloud condensation at constant mass, with substructure following the $\alpha(M)$ trend.
Klassen +17: Two MHD clouds with initial $\rho \sim r^{-1.5}$, (a) $\alpha=0.95$, no FB, 500 Msun  (b) $\alpha=0.56$, FB, 1200 Msun

(a) solid curve: $\alpha$ decreases with time as gravity gets stronger, and then $\alpha$ increases when the magnetic field gets strong and the cloud bounces.

(b) dotted curve: feedback keeps $\alpha$ and mass/flux constant
Cloud condensation after cloud growth, with substructure following

Pipe Nebula

Cha III

Milky Way Survey

Evolution with energy dissipation

\[ M \left[ M_{\odot} \right] \]

\[ \alpha_{\text{vir}} \]
Tosaki +14: NGC 1068

Virial parameter:

magenta=bound clouds,
green = unbound clouds

The spiral arm clouds are more gravitationally bound than the interarm clouds
Hirota +11: IC 342

A cloud’s self-gravity strengthens and its linewidth decreases as it passes into a spiral arm:
A two-component model of the ISM,

(a) Stirring everywhere from supernovae etc. and stellar dynamics (bars/spirals/shears)

→ produces a generally turbulent ISM, forming hierarchical density structure viewed differently with each tracer (HI, H$_2$, CO, HCN, dust, ...)

(b) Gravity takes over the motions wherever \( \Sigma \) gets large compared to \( (P/\pi G)^{1/2} \)
Li '17: The dissipation rate of a self-gravitating $\rho \sim 1/r^2$ cloud is higher than in the more uniform gas around it, so the ambient turbulent energy from SN, etc., cannot get into the cored-cloud and it collapses to form stars.
Hennebelle & Falgarone '12: Energy dissipation rate ($\rho \sigma^3 / R$) in $^{12}$CO clouds of the MW is independent of size and comparable to the dissipation rate in atomic gas. (This was the assumption of the Kritsuk +07 scaling theory)

Caldu-Prima '16: $\langle \sigma \rangle$ for CO on large scales (observed by single dish) is 2x larger than $\langle \sigma \rangle$ for CO on small scales, suggesting there is an energetic diffuse molecular gas.
What is the source of turbulence in observed molecular clouds: externally driven motions or gravity?

Drabek-Maunder +16: gravity, not outflows, drive turbulence in local clouds where $\alpha$ is low.

Turbulence is correlated with gravity

Outflow energy is not correlated with turbulence or gravity
Padoan +16a: SN only for 45 Myr and then SN+gravity. The cloud-to-cloud dispersion of the GMCs is made by SN even though the GMCs are dense.

The KE per unit mass of dense gas is 55% of that in the low density gas, so lots of SN energy gets into the GMCs

Before gravity (left) and after gravity (right): little change in pdfs for $\alpha$ and density

Padoan16b
Ibanez-Mejia +16: simulation with SN-driven turbulence at first and then gravity is turned on.

Gravity is needed for the observed $\sigma \sim \sqrt{R}$ and $\sigma \sim \sqrt{\Sigma R}$ relations.
Is the whole ISM turbulent?

Power spectra of LMC FIR (Spitzer) is a 2-piece power law covering the whole galaxy with a break at the inverse thickness (2D to 3D transition)
size of break
wavenumber

LMC: Herschel
Bournaud +10 simulations:

Spirals (gravity) cause 2D turbulent power spectrum at large scales

Gravity + feedback cause 3D power spectrum on small scales.

Feedback does not affect the power spectrum much (any source of turbulence energy gives the right PS):

Feedback+gravity maintain $Q \sim 1$ on scales $k^{-1} = \text{thickness}$

(Feedback is important to break apart clouds)
Combes +12: M33 power spectra from Herschel 100 mm

Too little FB: nothing to break apart the dense clumps formed by gravity

Too much FB: no small scale structure

Just right FB: good spirals, clouds, & power spectrum
Bournaud +10
LMC model
(half the galaxy shown)

Combes +12
M33 model

→ Large-scale structure (everything larger than the thickness)
gives the low-k power spectrum
Summary of energy sources

• Large scale (length > galaxy thickness) energy comes from stellar gravity, shear, galaxy collisions, etc.
  • e.g., spiral wave shear and shocks pump large-scale ISM turbulence
  • → If a simulation box has only a small region (<< spiral arms), then you miss this energy source

• Small scale (L<H) energy comes from feedback, cloud collisions (converging flows), magnetic instabilities, cosmic ray instabilities, etc., and more gravity (in collapsing GMCs etc).

• The large scale (2D) turbulence cascades to the small scale (3D) turbulence, but vice versa?
  • Grisdale +17 gets no large-scale power law in a galaxy simulation without SDW
Implications for stellar birth places and times

- Gas is hierarchical, so stars are born in hierarchical star complexes

- Gas gives position and velocity; stars give position and age
Cumulative number or regions versus size in LEGUS survey.

Slope = fractal D

Spirals (dotted): $D \sim 1.3$ overall (porous)
Dwarfs (dashed): $D \sim 1.2$ overall (porous)
Starbursts (solid): $D \sim 1.7$ (area filling)

Elmegreen +14
Cumulative number of regions versus size in LEGUS survey.

Slope = fractal D

Spirals (dotted): $D \sim 1.3$ overall (porous)
Dwarfs (dashed): $D \sim 1.2$ overall (porous)
Starbursts (solid): $D \sim 1.7$ (area filling)

Individual SF regions have steep slopes ($D \sim 2$) for all galaxy types.

Hierarchical star complexes are a standard unit of SF
Gouliermis +17: NGC 1566 FUV stellar density contours from the LEGUS HST survey (left) and the power-law distribution of contour size.
The 2-point correlation function for clusters is a power law (scale free structure in the stars) and the slope decreases with age. → hierarchy disappears with age as stars move

(see also Bastian +09, Scheepmaker +09, Gieles +11, Baumgardt +13, Pellerin +07 +12; Gouliermis +’14, ...)

Gieles +09: SMC

Grasha +15: NGC 628 (LEGUS)
Grasha +17: (LEGUS): age difference between cluster pairs increases with separation up to a few 100 pc and 20-100 Myr ($\Delta t \sim \Delta R/\sigma(R) \sim R^{0.5}$)
Grasha +17: The ratio of the maximum correlated size to the maximum correlated time ("Velocity") divided by the average shear velocity ($V_s$) is the same for all galaxies.

- shear destroys the correlation as the regions age
- no bulk collapse of SF regions
Summary

• $\sigma \sim 0.1(R\Sigma)^{0.5}$ (standard units) if clouds are self-gravitating, and higher,
  $\sigma \sim 0.1(R\Sigma)^{0.5}(1+3.3\frac{P_{\text{external}}}{P_{\text{self-gravity}}})^{0.5}$ if clouds are diffuse

• $\alpha$ is another way of saying the same thing: $\alpha \sim (1+3.3\frac{P_{\text{ext}}}{P_{\text{self-gravity}}}) \sim M_{\text{survey}}^{-0.5}$

• Scaling is from pervasive turbulence with locally strong self-gravity
  • turbulent energy sources range from large-scale stellar forcing (SDW/bars, shear) to point sources (stellar FB), with an energy cascade to smaller scales + cosmic rays + instabilities + ... bridging the gaps
  • gravity becomes important whenever $\Sigma > (P/\pi G)^{0.5}$

• Young stars follow the spatial and temporal structure of the turbulent ISM