Turbulence in interstellar molecular clouds: observational properties

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New Challenges in Turbulence Research / March 2014

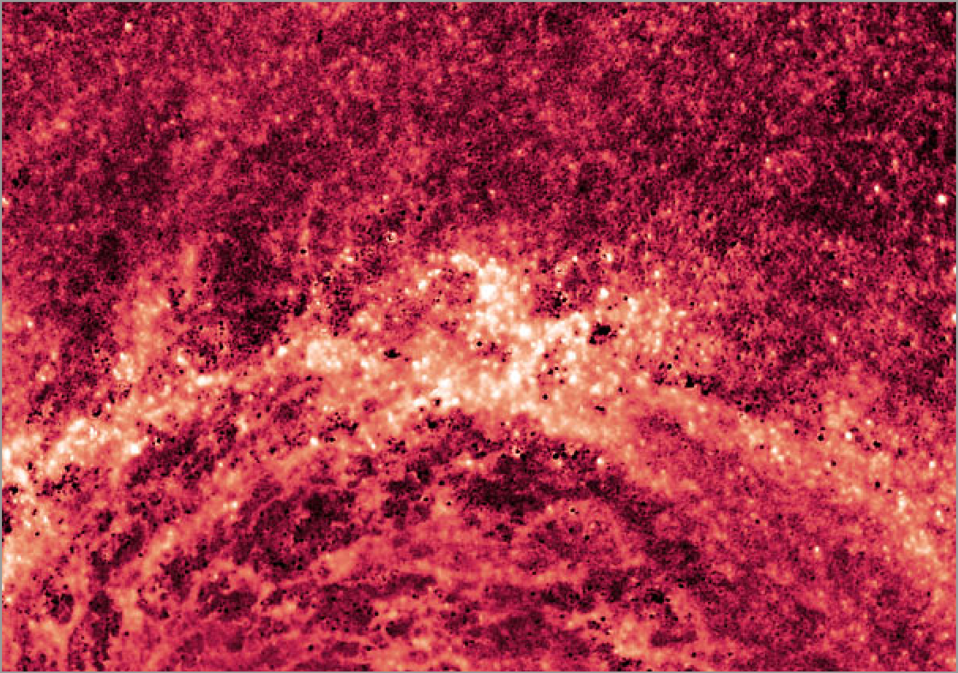
Introduction

What this talk is not about

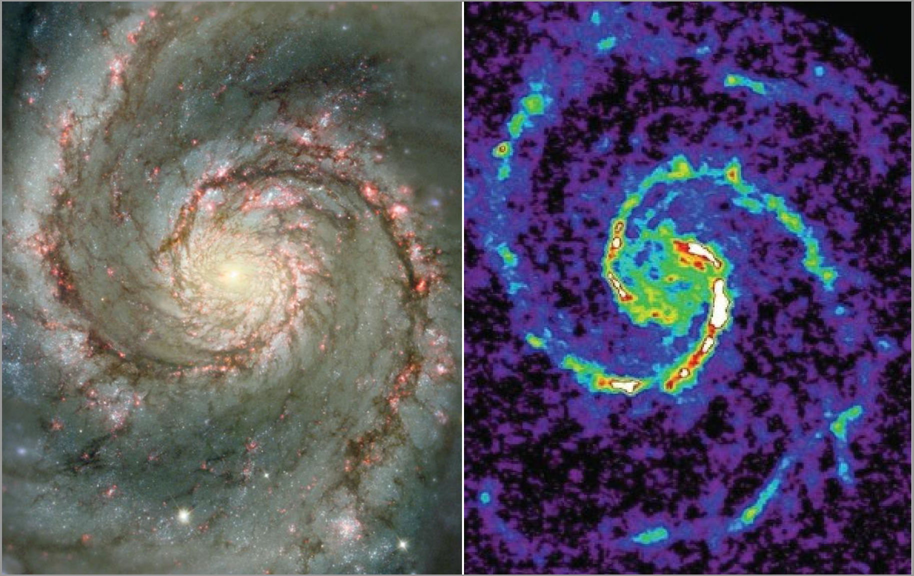
- theoretical aspects of turbulence
- *in situ* or 3D measurements

What this talk is about

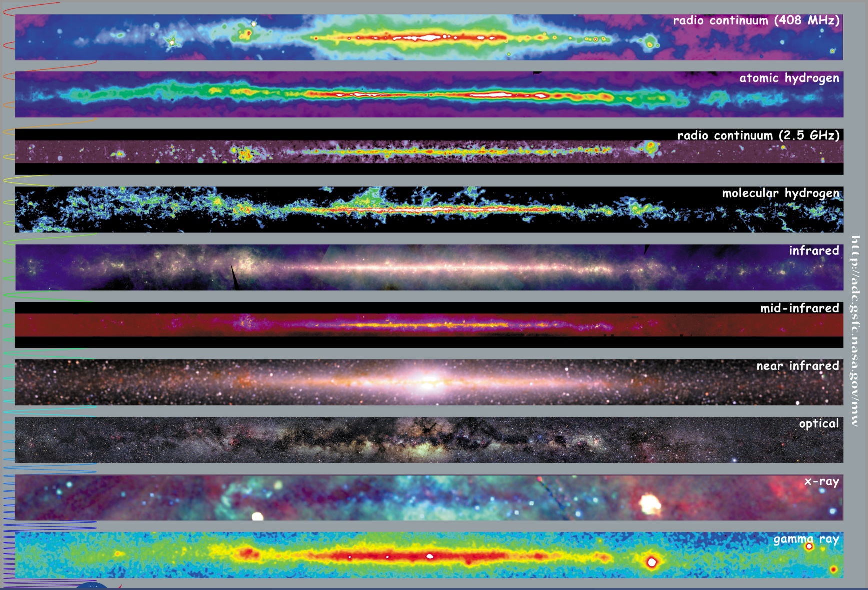
- role of turbulence in the interstellar medium
- observations and remote sensing of turbulence



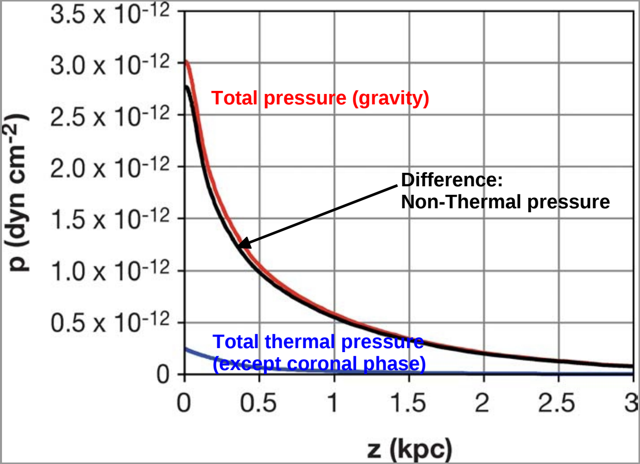
Cold Molecular Gas



The Multiwavelength Milky-Way



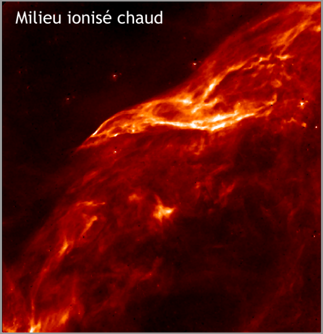
Observational evidences: Pressure



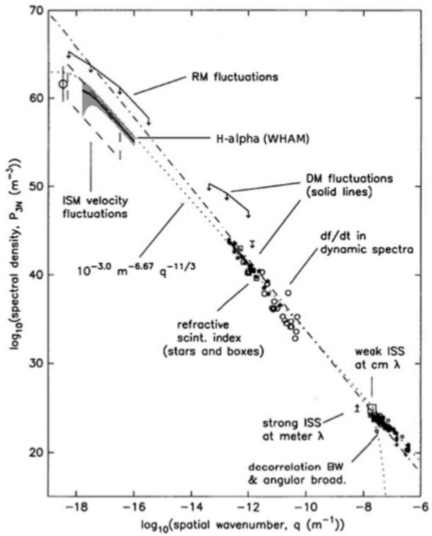
Adapted from D. Cox, ARA&A 2005

Non-thermal pressure: $P_{\rm CR} \sim P_{\rm nth} \sim P_{\rm mag} \approx 1 \times 10^{-12}\ {\rm dyn\,cm^{-2}}$

Power laws

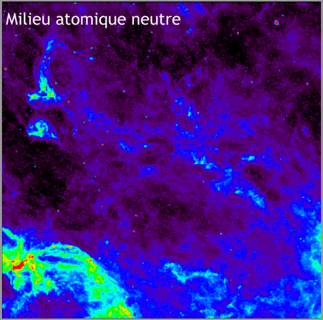


- Local ISM
- 3-D power-spectrum of e^-–density fluctuations
- Power-law with index very close to K41 prediction (-11/3)

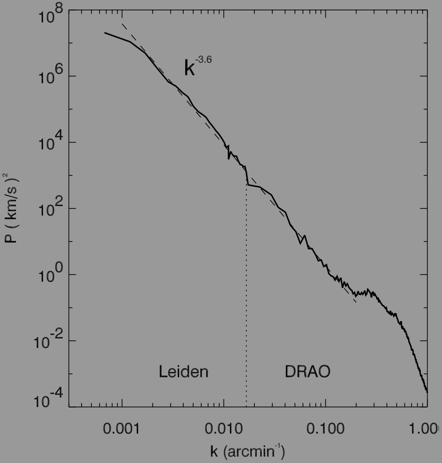


Armstrong et al. (1995)

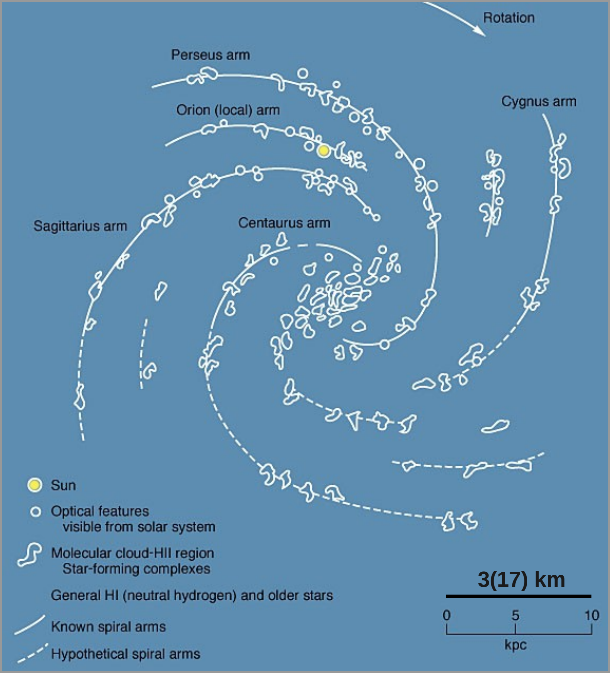
Power laws



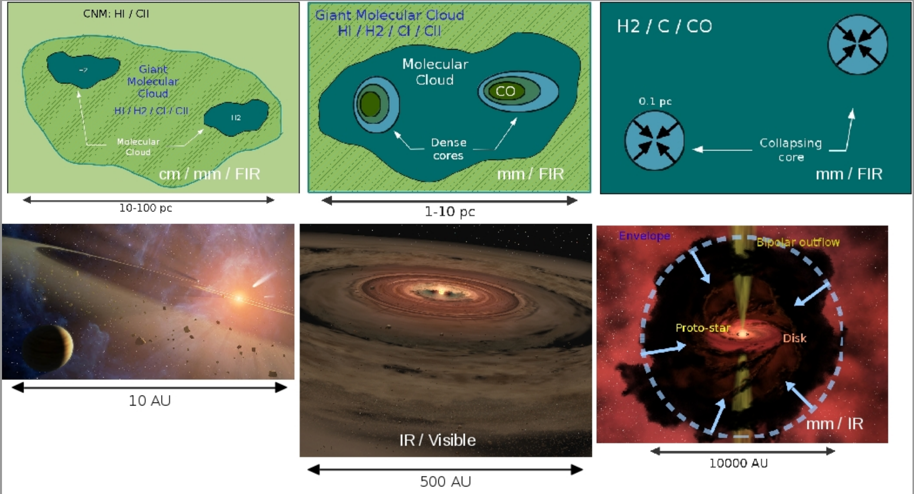
- Cold Neutral Medium
- Traced by hyperfine transition of HI (λ21cm)
- Intensity power spectrum



Miville-Deschênes et al. (2003)


Rotation
Perseus arm
Orion (local) arm
Cygnus arm
Sagittarius arm
Centaurus arm
Sun
Optical features
visible from solar system
Molecular cloud-HII region
Star-forming complexes
General HI (neutral hydrogen) and older stars
Known spiral arms
Hypothetical spiral arms
3(17) km
0
5
10
kpc

The dense ISM and the birth of stars and planets



1 pc = 2(5) AU

Questions

- Is the cold molecular gas part of the turbulent cascade ?
- Are molecular clouds turbulent structures ?
- Consequence on star formation ?
  - Turbulence support must be dissipated for stars to form
  - However, not too fast.
- Questions: how ? at which rate ? in which structures ?

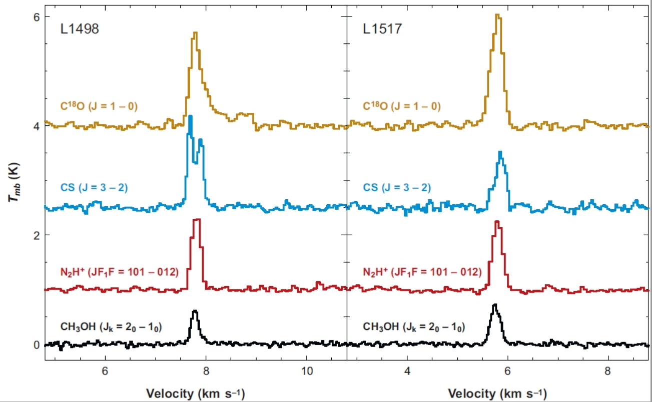
Interstellar Medium (ISM)

- gas and dust
- fully ionized (hot, tenuous, atomic)
- neutral (cold, dense, atomic/molecular)
- out of equilibrium
- observations of the ISM: spectroscopy, continuum

Molecular clouds: observations

- Single-dish
- Interferometer
- Caracteristic: high spectral resolution

Doppler shift and velocity measurements



- Resolving power: $\nu/\delta\nu > 5\times10^6$
- At $\nu = 100$ GHz, $\delta v \leq c/5\times10^6 = 60\,\mathrm{m\,s^{-1}}$
- Sound speed at 10-20 K in molecular gas: $v_{\rm th} \sim 200\,\mathrm{m\,s^{-1}}$

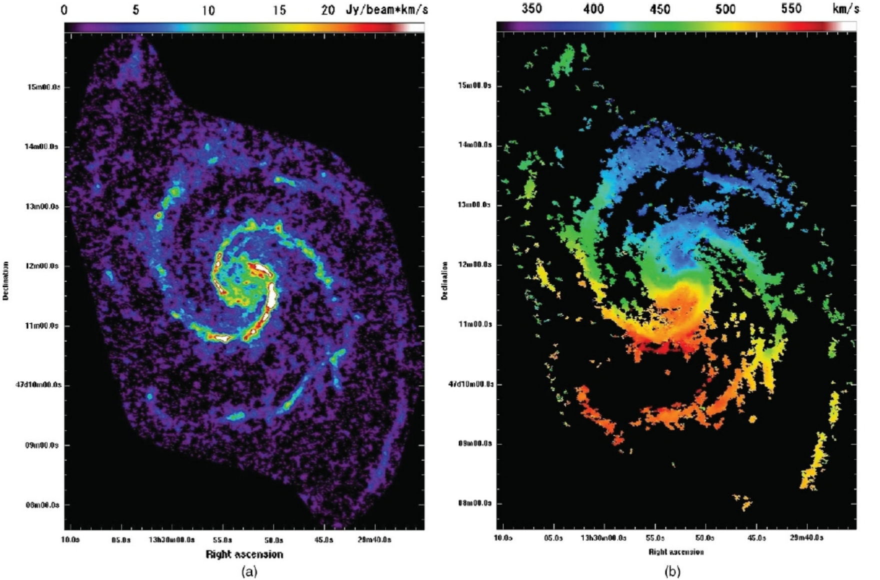
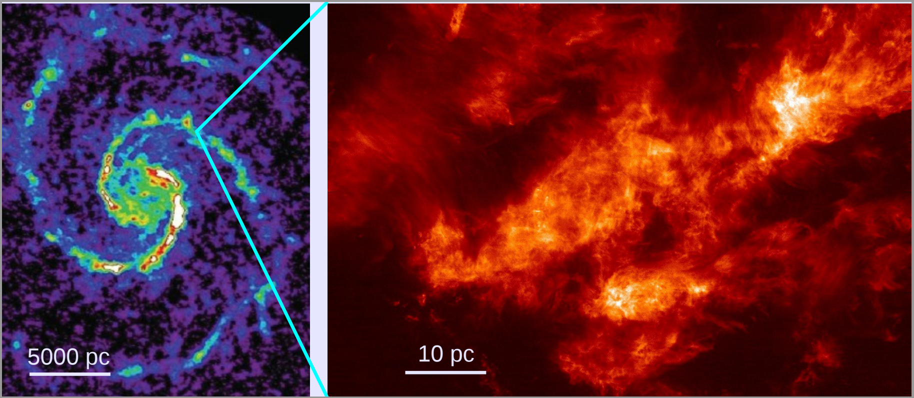


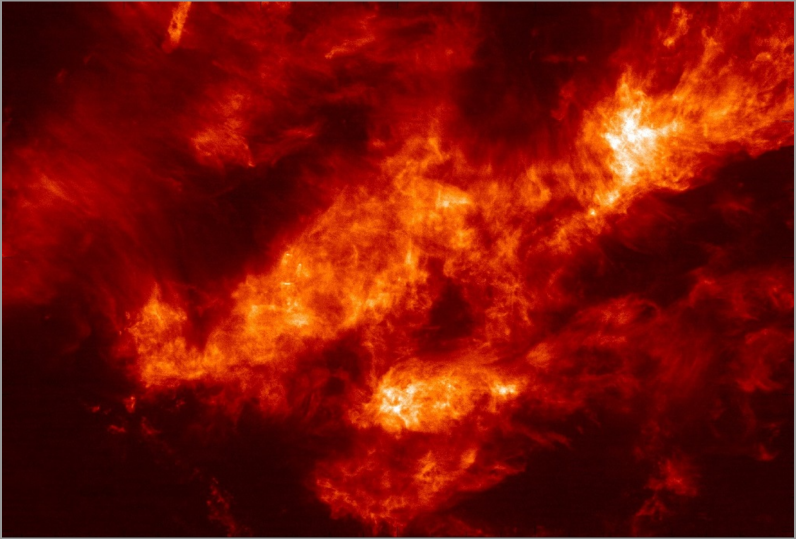
Figure 1. (a) Integrated intensity map of CO(J = 1–0) emission of the entire disk of M51. The 6′.0 × 8′.4 region was mosaiced in 151 pointings at 4″ resolution with the CARMA interferometer. The total power and short-spacing data are obtained with the On-The-Fly mapping mode of the BEARS multi-beam receiver on the Nobeyama Radio Observatory 45 m telescope (NRO45). The CARMA and NRO45 data are combined in the Fourier space. The maps clearly detect GMCs over the entire disk for the first time, including both the prominent spiral arms and interarm regions. (b) Velocity field. Significant shear motions are seen at tangential positions (P.A. of the disk kinematic major axis is −11 deg).

Molecular clouds: aspect



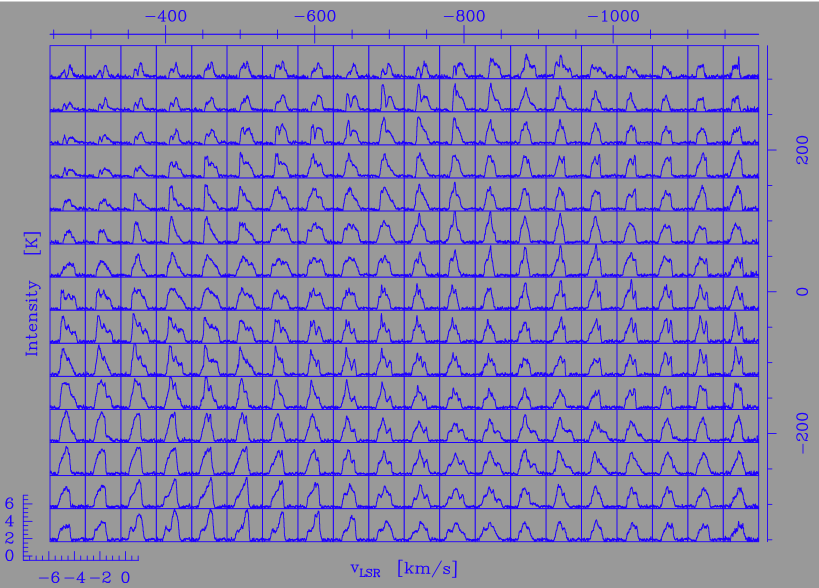
- Beautiful; complex; contrasted
- Filamentary
- Full of emptiness: volume filling factor $\sim 1\%$

Spectral maps: ppv cubes

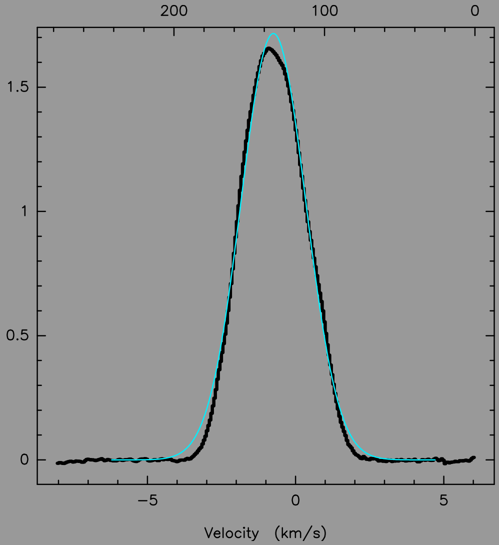


Few millions spectra

Maps of spectra



Average spectra



Foreword

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 114 SEPTEMBER 1951 NUMBER 2

THE EVOLUTION OF GALAXIES AND STARS

C. F. von Weizsäcker
Max Planck Institut, Göttingen

Received May 17, 1951

ABSTRACT

I. Aims of the theory.—A hydrodynamical scheme of evolution is proposed, confined to events after the time when the average density in the universe was comparable to the density inside a galaxy at our time.

II. Hydrodynamical conditions.—Gas in cosmic space is moving according to hydrodynamics, mostly in a turbulent and compressible manner. Dust is carried with the gas, probably by magnetic coupling. Star systems cannot be described hydrodynamically and hence do not show turbulence and supersonic compressibility.

III. The spectral law of incompressible turbulence.—The relative velocity of two points at a distance l is proportional to $l^{1/3}$. This is deduced from the picture of a hierarchy of eddies.

IV. Compressibility and interstellar clouds.—A hierarchy of clouds is considered.

Failed to catch on... although much of this talk was there already.

Mon. Not. R. astr. Soc. (1981) **194**, 809–826

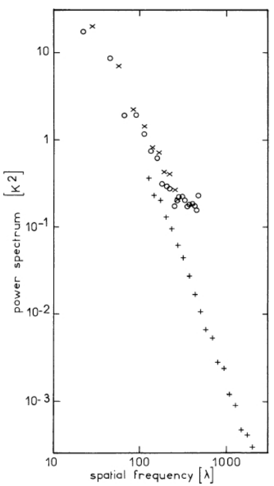
Turbulence and star formation in molecular clouds

Richard B. Larson *Yale University Observatory, Box 6666, New Haven, Connecticut 06511, USA*

The spatial power spectrum of galactic neutral hydrogen from observations of the 21-cm emission line

J. Crovisier[1] and J. M. Dickey[1,2*]

[1] Observatoire de Meudon, F-92190 Meudon, France
[2] National Radio Astronomical Observatory, Charlottesville, Virginia 22901, USA



30 years later. Did catch on.

Crovisier & Dickey (1983)

Observational Evidences: Reynolds number

- Assuming that dissipation $\leftarrow$ molecular viscosity
- $\mathrm{Re} = VL/\nu$, $\nu = v_{\mathrm{th}}\lambda$, $\lambda = 1/n\sigma$

Table 1: Reynolds number in the neutral medium.

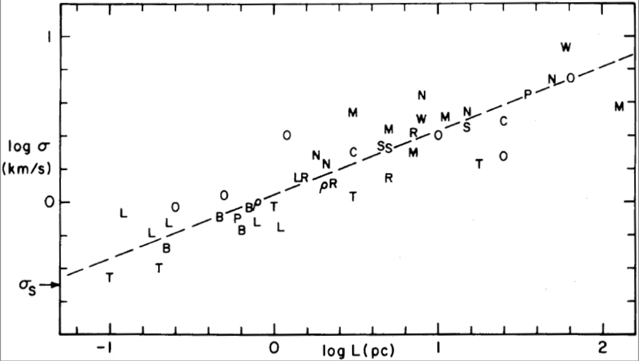
		Atomic	Molecular	Cores
L	pc	30	3	0.1
T	K	80	30	10
n	cm^{-3}	30	300	3000
$\sigma^{\dagger}$	$\times10^{-15}\ \mathrm{cm}^2$	5	10	10
ℓ	AU	0.4	0.02	0.002
v_L	$\mathrm{km\ s}^{-1}$	3.5	1	0.1
v_{th}	$\mathrm{km\ s}^{-1}$	1.4	0.6	0.3
$\nu^{\ddagger}$	$\mathrm{cm}^2\ \mathrm{s}$	1.0×10^{18}	2.1×10^{16}	1.3×10^{16}
L/ℓ		1×10^{7}	3×10^{7}	1×10^{7}
v_L/v_{th}		2.5	1.7	0.3
Re_L		3×10^{7}	5×10^{7}	2.3×10^{5}
$\eta^{\S}$	AU	15	1.0	0.3

† σ is the cross-section for elastic collisions between H or H_2 atoms. From Spitzer (1978).
‡ The molecular viscosity is $1.1\times10^{17}\,T^{1/2}$ in the atomic gas, and $4.0\times10^{15}\,T^{1/2}$ in the molecular gas.
§ The dissipation scale is estimated as $\eta = L\mathrm{Re}_L^{-3/4}$.

Note: injection scale might be (much) larger than L

Scalings: velocity dispersion – size

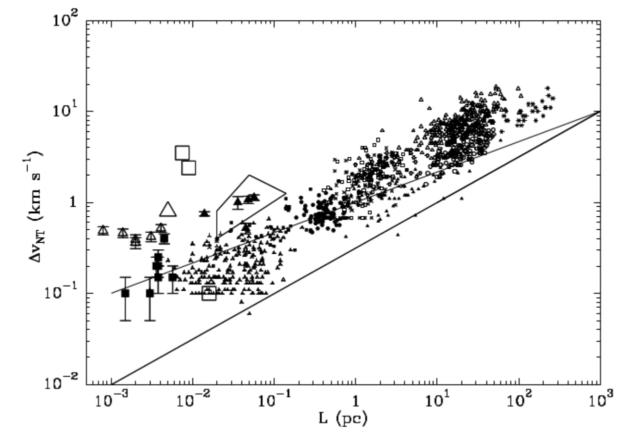
- Velocity dispersion in molecular clouds
- $\sigma \propto L^{0.38}$ close to 1/3 from K41
- suprathermal



Larson (1981)

Scalings: velocity dispersion – size

- Current picture
- $\sigma \propto L^{\alpha}$, $\alpha = 1/3 \ldots 1/2$.



Falgarone et al. (2009)

Velocity statistics

- Essentially two-point statistics: compute the PDF of increments of measurable quantities
- Main issue: not so many measurable quantities
    - line observations: line intensity, integrated intensity, velocity
    - continuum observations: integrated amount of material (column density)

Centroid Velocity Increments method

- extract a single value from each spectrum: basically, 1st order moment (Lis et al 1996, Pety et al 2003)

$$C(x,y) = \int_{v_1}^{v_2} T(x,y,v) v \, \mathrm{d}v / \int_{v_1}^{v_2} T(x,y,v) \, \mathrm{d}v$$

- determine the increments of centroid velocity (CVI)

$$\delta C(\vec{r}, \vec{l}) = C(\vec{r} + \vec{l}) - C(\vec{r})$$

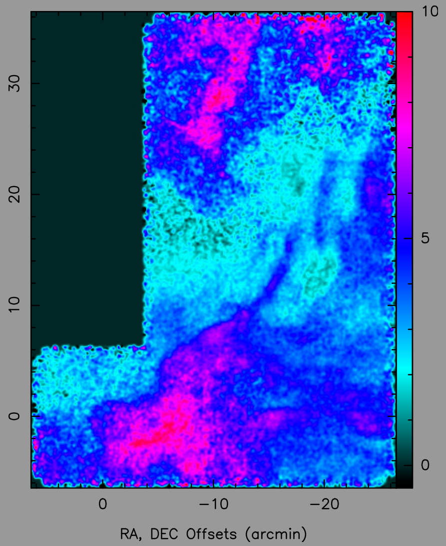
- Average azimuthally

$$\delta C_l$$

- compute Probability Density Function of CVI

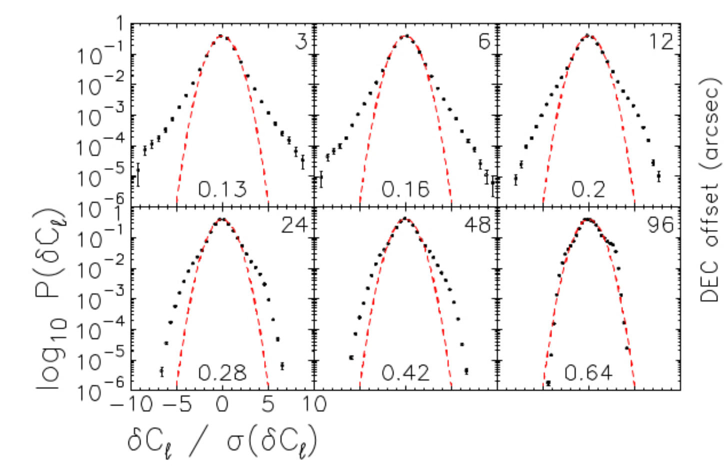
$$\mathcal{P}(\delta C_l)$$

The Polaris molecular cloud

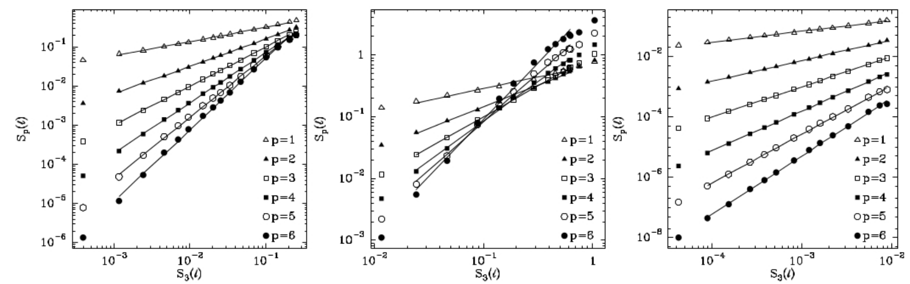


$\approx$ a million spectra, with $\nu/\delta\nu \sim 10^7$

PDF of CVI

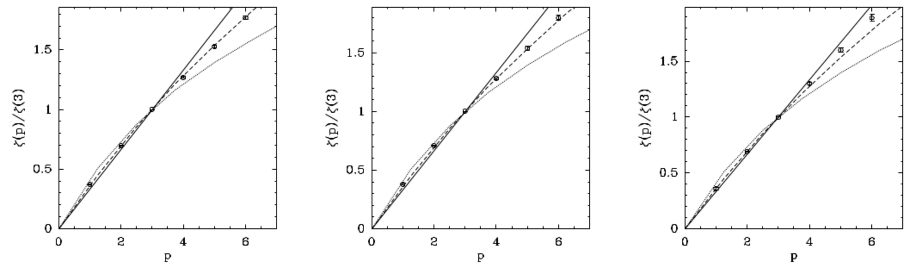

3
6
12
24
48
96
0.13
0.16
0.2
0.28
0.42
0.64
$\log_{10} P(\delta C_\ell)$
DEC offset (arcsec)
$\delta C_\ell / \sigma(\delta C_\ell)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
−10 −5 0 5 10

Structure functions



$$S_p(l) = \int_0^\infty |\delta C_l|^p \mathcal{P}_n(|\delta C_l|)\ \mathrm{d}(|\delta C_l|) \propto l^{\zeta(p)}$$

Structure functions



- $\tilde{\zeta}_p = \zeta(p)/\zeta(3) = \frac{p}{9} + C\left[1 - \left(1 - \frac{2}{3C}\right)^{p/3}\right]$ (She&Levêque 1994, Dubrulle 1994)
- $C = 2$ in incompressible
- $C = 1$ in shock-dominated turbulence dissipation
- But depends on forcing (solenoidal vs compressive, Federrath et al A&A 2010)

Regions of viscous dissipation

- Rate of viscous dissipation per unit mass:

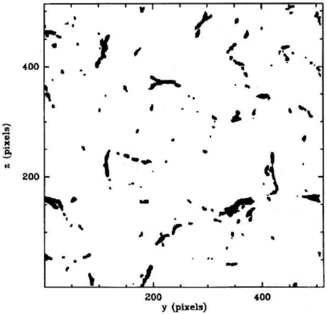
$$\langle \epsilon_d \rangle = \frac{1}{2} \nu \left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_k}{\partial x_i} \right)^2$$

- In terms of the vorticity $\omega = \boldsymbol{\nabla} \times v$:

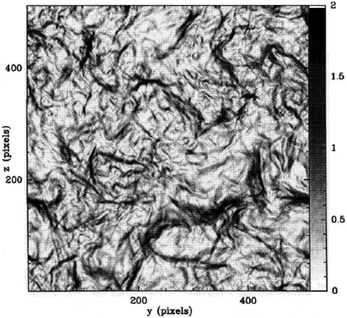
$$\langle \epsilon_d \rangle = \nu |\boldsymbol{\nabla} \times v|^2$$

- Idea: trace the vorticity... but only one velocity component in two directions $(v_z(x, y))$
- Chemical tracers: CH+ as traced with the Herschel satellite (Joulain et al 1998, Godard et al 2009, Falgarone et al 2010)

Regions of turbulence dissipation



Subset of largest line Centroid Velocity increments (CVIs)

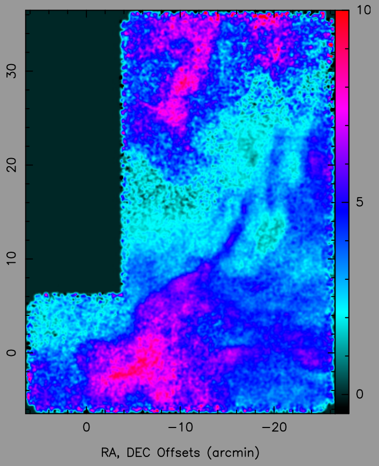


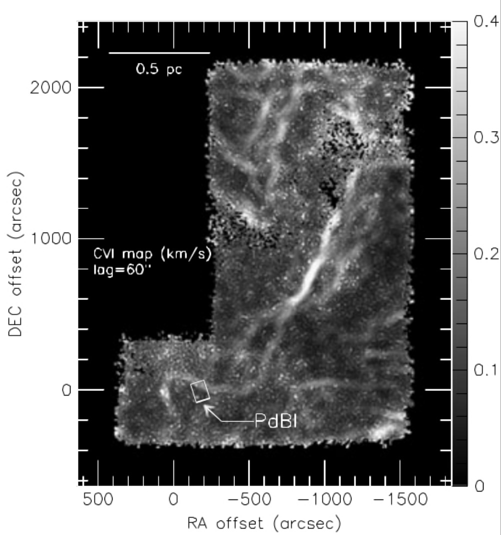
Subset of largest $\langle \Omega_{sky} \rangle_{\rm los}$

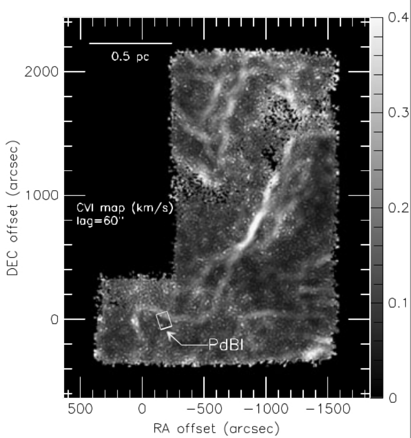
Lis *et al* 1996

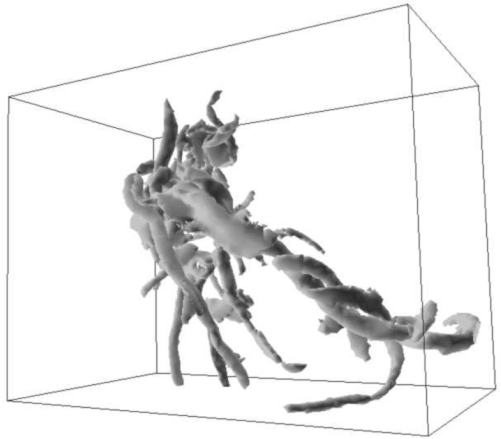
- mildly supersonic hydrodynamic (Porter et al 1994)
- Large CVI regions pinpoint large shear-regions

Extreme-CVI structures in the Polaris Cloud









Moisy & Jimenez 2004

- clustering of intense shear structures
- suggestive similar structures in high-Re turbulence in the Polaris cloud

Multiphasic turbulence

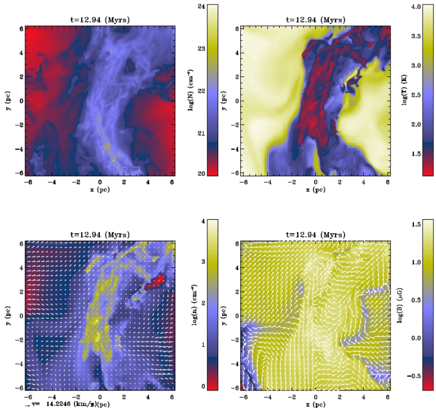


Fig. 3 Column density *(top left)*, and cuts of the density with projected velocity field *(bottom left)*, temperature *(top right)* and magnetic field *(bottom right)* of a simulation snapshot of molecular cloud formation (Hennebelle et al. 2008). While the total magnetic intensity is shown, the arrows indicate the direction of the field in the XY plane.

Hennebelle et al A&A 2008

- Biphasic equation of state
- Generates cold structures embedded into warm gas

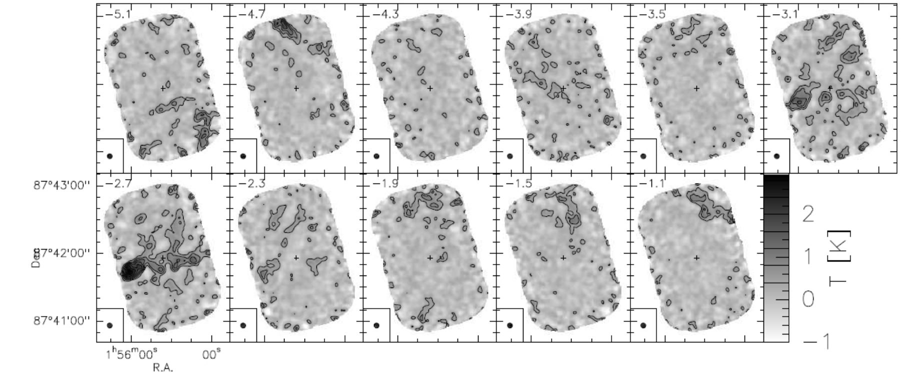
Models of turbulence in molecular clouds

- compressible / incompressible
- HD / MHD
- decaying / forced
- self-gravity, chemistry, thermal balance, etc
- Pr$= \nu/\eta \sim 10^6$ in molecular clouds

Difficulties

- Spatial dynamics:
  - huge requirement to numerical simulations
  - role of gravity
  - role of magnetic fields (big observational problem)
- Chemistry (e.g. combustion)
  - CO observations in the diffuse remain unexplained
  - coupling of a large number of processes
- Supersonic turbulence

The dissipation scale



Falgarone et al 2009

- Velocity structures at at milli-pc scale (PdBI)
- milli-pc $\approx 100\text{AU} \approx 1.5 \times 10^{13}$ m)
- ALMA observatory should go down to ~ 15 AU spatial resolution, close to the molecular viscosity dissipation scale...

The dissipation scale

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Armstrong, J. W., Rickett, B. J., & Spangler, S. R. 1995, ApJ, 443, 209

Crovisier, J. & Dickey, J. M. 1983, A&A, 122, 282

Falgarone, E., Pety, J., & Hily-Blant, P. 2009, Astronomy & Astrophysics, 507, 355

Gibson, S. J. & Nordsieck, K. H. 2003, ApJ, 589, 347

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

Miville-Deschênes, M., Joncas, G., Falgarone, E., & Boulanger, F. 2003, A&A, 411, 109