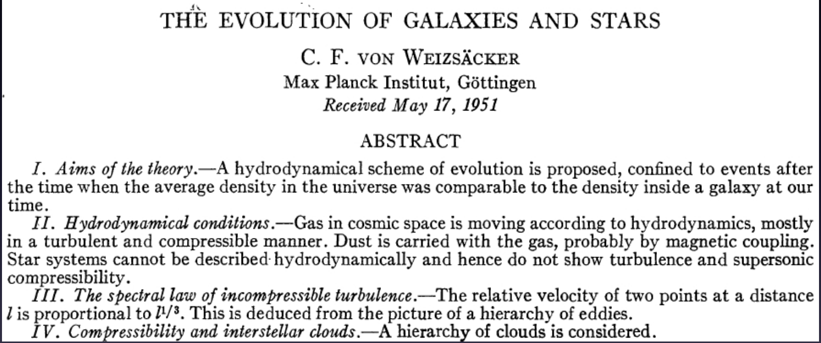
Structure of turbulence intermittency in molecular clouds

P. Hily-Blant
IPAG

Atelier OSUG / June 18th, 2012

Introduction



THE EVOLUTION OF GALAXIES AND STARS

C. F. von Weizsäcker
Max Planck Institut, Göttingen

Received May 17, 1951

ABSTRACT

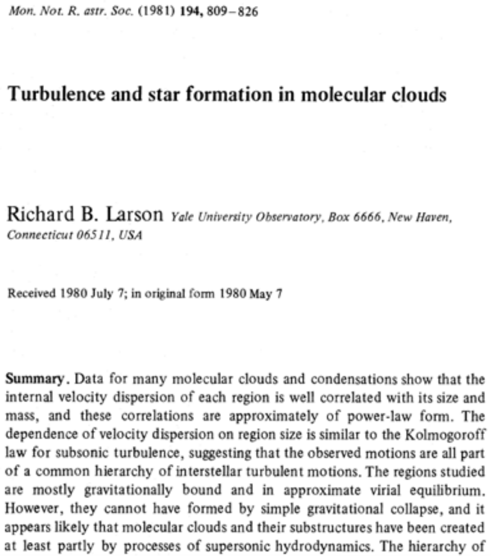
I. Aims of the theory.—A hydrodynamical scheme of evolution is proposed, confined to events after the time when the average density in the universe was comparable to the density inside a galaxy at our time.

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...



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

Turbulence and star formation in molecular clouds

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Received 1980 July 7; in original form 1980 May 7

Summary. Data for many molecular clouds and condensations show that the internal velocity dispersion of each region is well correlated with its size and mass, and these correlations are approximately of power-law form. The dependence of velocity dispersion on region size is similar to the Kolmogoroff law for subsonic turbulence, suggesting that the observed motions are all part of a common hierarchy of interstellar turbulent motions. The regions studied are mostly gravitationally bound and in approximate virial equilibrium. However, they cannot have formed by simple gravitational collapse, and it appears likely that molecular clouds and their substructures have been created at least partly by processes of supersonic hydrodynamics. The hierarchy of

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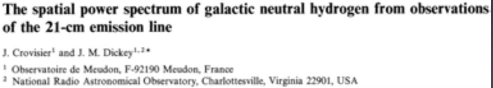


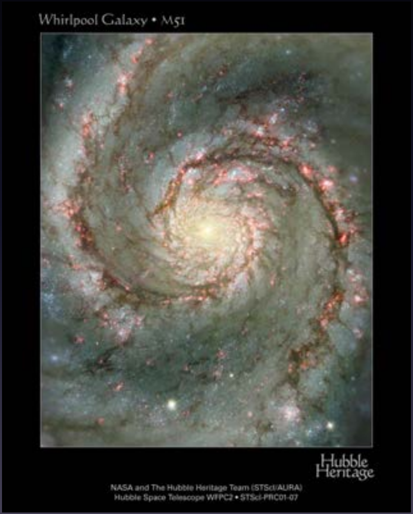
The spatial power spectrum of galactic neutral hydrogen from observations of the 21-cm emission line

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

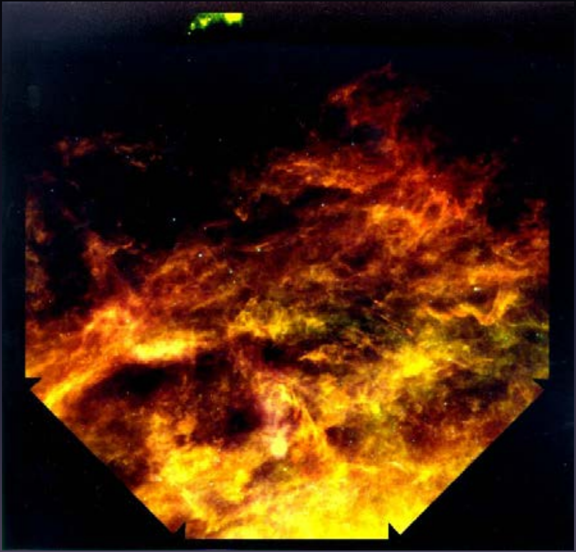
The turbulent ISM: Observations

- Several components or phases (HIM, WIM, WNM, CNM, MM)
- Different volume fractions and thermal properties → thermal pressure
- Vertical structure of the Milky Way → gravitational potential



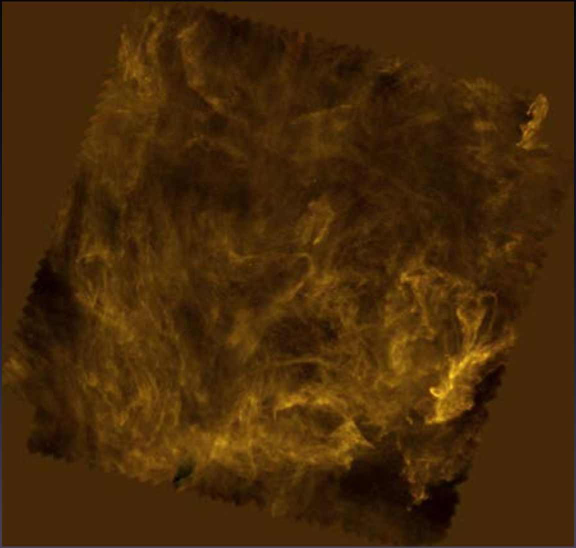
NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Cold atomic clouds (100 pc)



IRAS: complex cirrus clouds

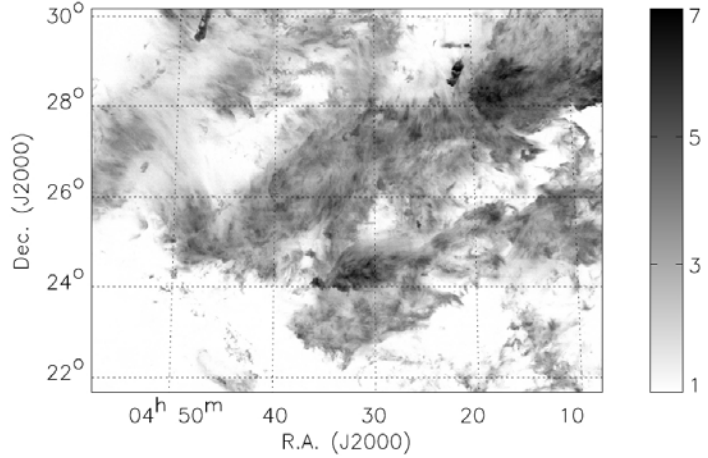
Molecular clouds (30 pc)



Herschel Satellite

The gaseous component

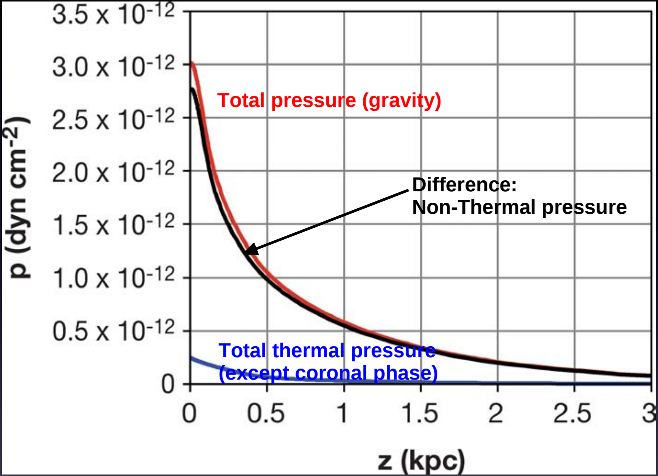
Large-scale molecular structures (few pc)



Taurus molecular cloud, Goldsmith et al 2008

CO emission is filamentary, lacunary

1) Pressure

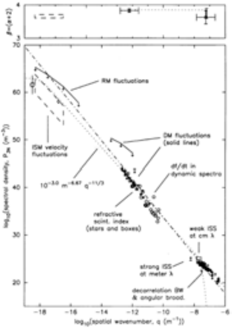


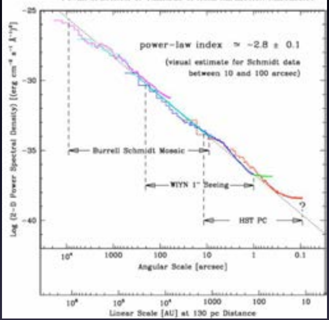
Adapted from D. Cox, ARA&A 2005

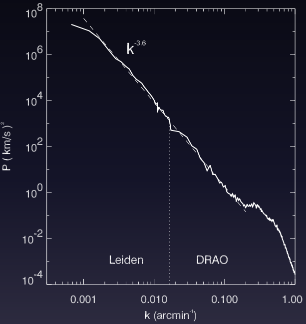
Non-thermal pressure:

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

2) Power laws in various phases







Ionized gas: $n_{3D}(e^{-})$

Armstrong et al. (1995)

HII regions

Gibson & Nordsieck (2003)

Cold Neutral Medium (CNM)

Miville-Deschênes et al. (2003)

- The ISM is, as a whole, turbulent
- The cold ISM is also turbulent

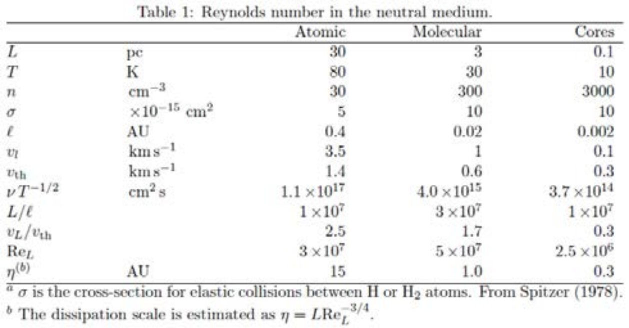


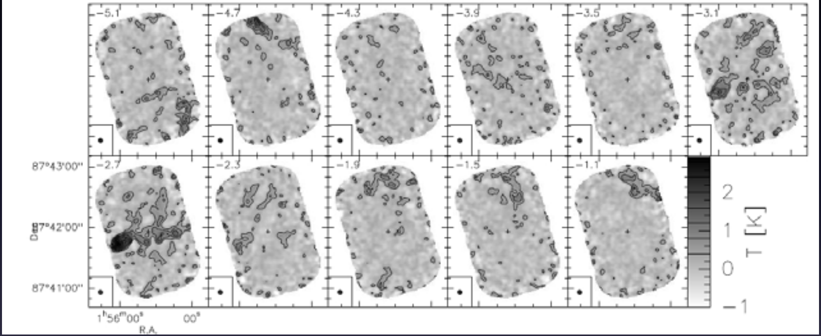
Table 1: Reynolds number in the neutral medium.

		Atomic	Molecular	Cores
L	pc	30	3	0.1
T	K	80	30	10
n	cm^{-3}	30	300	3000
σ	$\times 10^{-15}\ \mathrm{cm}^2$	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
$\nu T^{-1/2}$	$\mathrm{cm}^2\,\mathrm{s}$	1.1×10^{17}	4.0×10^{15}	3.7×10^{14}
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	2.5×10^6
$\eta^{(b)}$	AU	15	1.0	0.3

[a] σ is the cross-section for elastic collisions between H or H_2 atoms. From Spitzer (1978).

[b] The dissipation scale is estimated as $\eta = L\mathrm{Re}_L^{-3/4}$.

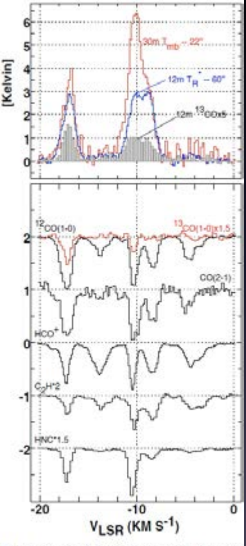
2) TSMS (milli-pc $\approx 100\mathrm{AU} \approx 1.5 \times 10^{13}$ m)



Falgarone et al 2009

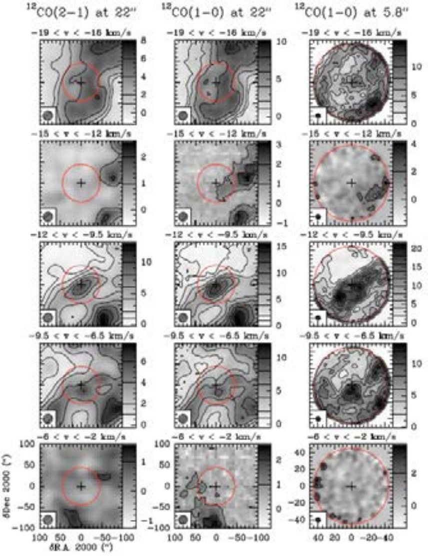
Filaments at milli-pc scale (PdBI)

3) TSMS



1. Emission and absorption spectra toward B0355+508

Absorption spectra towards NRAO150



IRAM30m+PdBI, Pety et al 2010

Viscous dissipative structures

- Rate of viscous dissipation per unit mass:

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

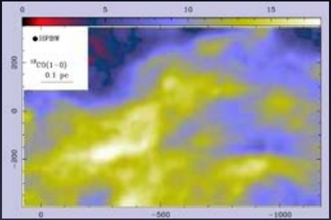
- In terms of the vorticity $\omega = \boldsymbol{\nabla} \times v$:

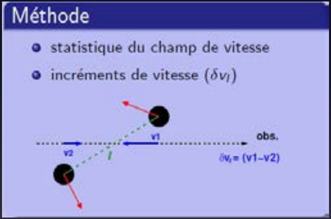
$$\langle \epsilon_d \rangle = \nu |\boldsymbol{\nabla} \times v|^2$$

- 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)

Centroid Velocity Increments method

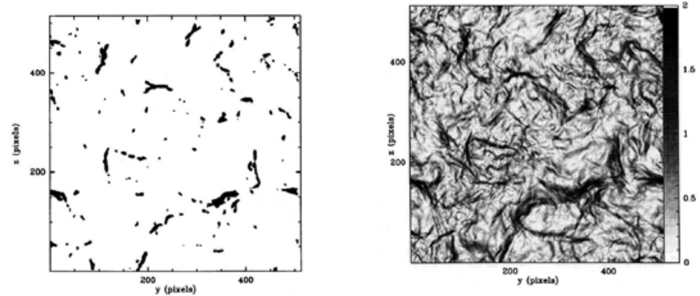
- determine the two-point statistics (Lis et al 1996, Pety et al 2003)





Méthode

- statistique du champ de vitesse
- incréments de vitesse (δv_l)



Subset of largest line Centroid Velocity increments (CVIs)

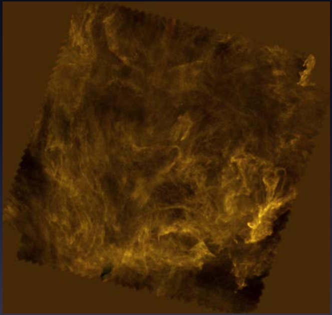
Subset of largest $\langle \Omega_{sky} \rangle_{\rm los}$

Lis *et al* 1996

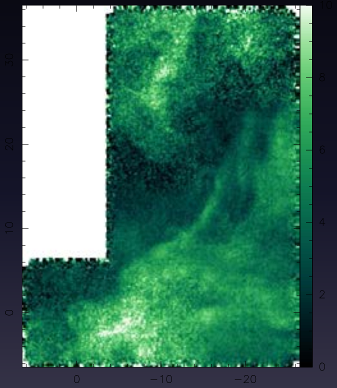
Lis et al 1996

Large CVI regions pinpoint large shear-regions

The Polaris Flare

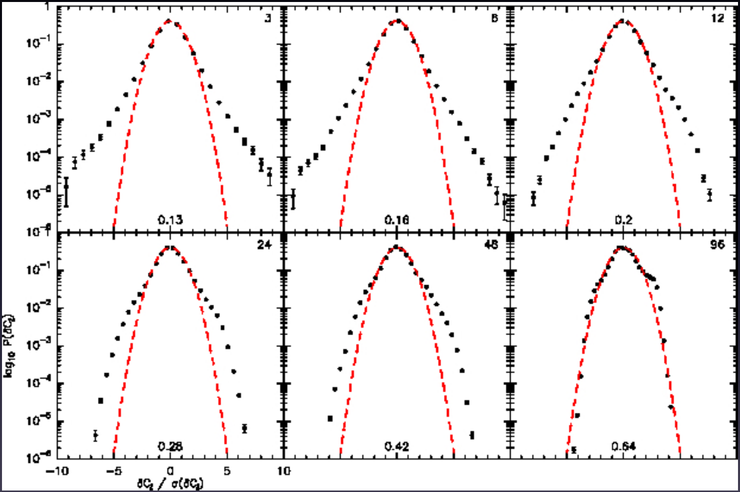


Herschel



Gas emission

Make a pdf of these values for various lags



Non-Gaussian wings show up as the lags decreases

Statistics of the velocity field

$$S_p(l) = \int \delta C_l^p P(\delta C_l)\,\mathrm{d}(\delta C_l) \propto l^{\zeta_p}$$

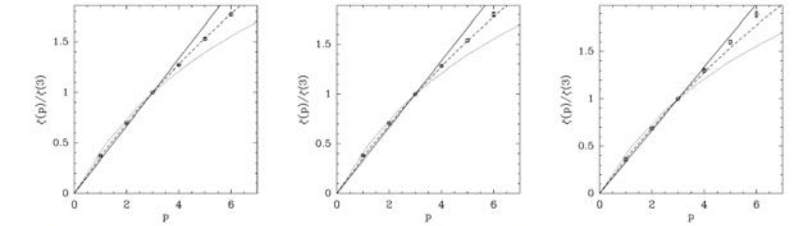
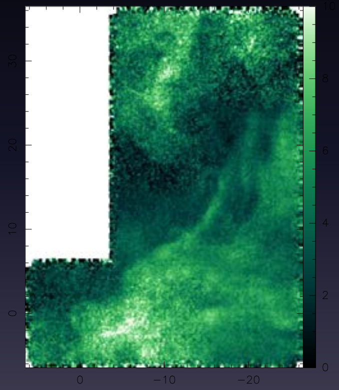


Fig. 14. Values of the exponents of the structure functions (see Fig. 8) with error bars (see Table 3). For comparison, the K41 (full), SL94 (dashed), and B02 (dotted) scalings are indicated. *From left to right*: Polaris (IRAM), Polaris (KOSMA), Taurus.

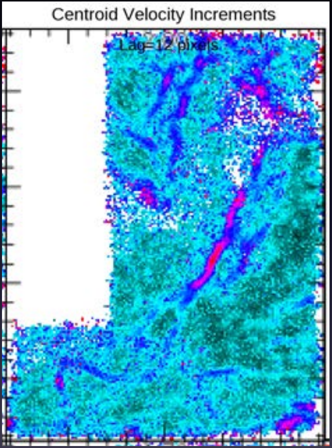
Hily-Blant et al 2008

Deviations from superAlfvénic predictions

E-CVI structures in the Polaris Flare

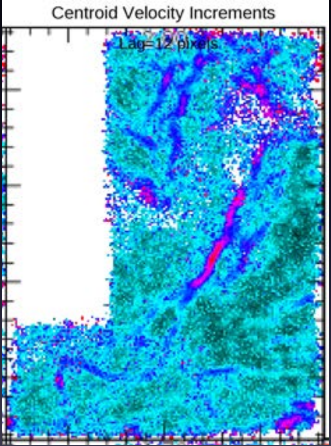


Integrated intensity

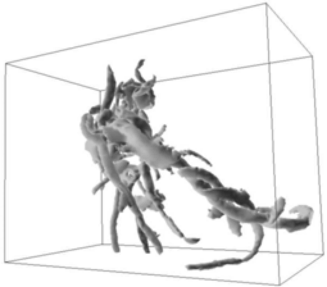


CVI structures

E-CVI structures in the Polaris Flare



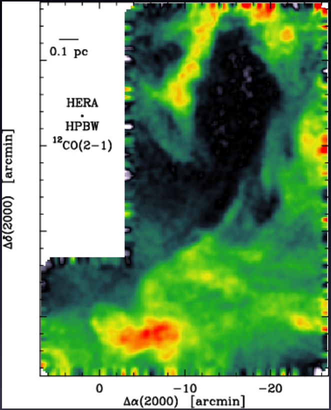
in prep



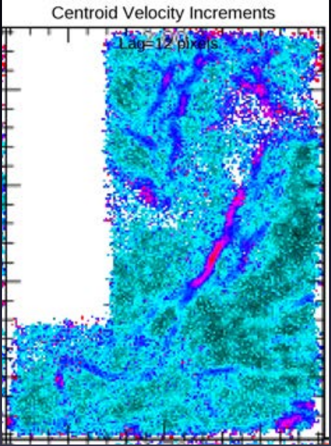
Moisy & Jimenez 2004

- Turbulence in the ISM, though strongly suggested, is still to be proved
- What do numerical simulations tell regarding dissipative structures ?
- Basic properties of the turbulence are waiting further numerical experiments and new observations with better sensitivity and spatial resolution
- ALMA will barely resolve out the viscous dissipative scale in molecular gas (1 AU), but the question of how far do small-scale in the molecular gas is crucial.

4) Pure velocity structures



Hily-Blant & Falgarone 2009



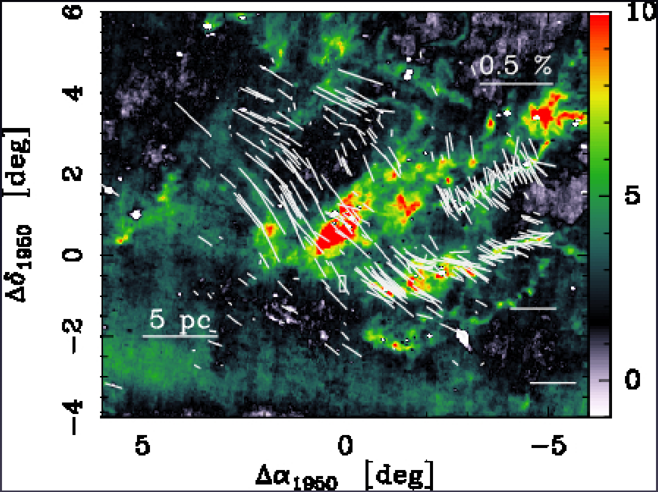
Clabaut et al, in prep

Filamentary (in projection) velocity structure (no density enhancement)

Magnetic fields

- Globally in the ISM, components ≈ in equipartition: $P_{\rm dyn} \sim P_{\rm mag} \sim P_{\rm CR} \lesssim 10^{-12}$ dyn ${\rm cm}^{-2} \approx 10^4$ K ${\rm cm}^{-3}$
- $P_{\rm dyn} \approx 10^{-12}$ dyn ${\rm cm}^{-2}$: $\sigma_v \sim 6\ {\rm km\,s}^{-1}$
- $P_{\rm mag} \approx 10^{-12}$ dyn ${\rm cm}^{-2}$: $B \sim 5\ \mu$G
- $v_A \sim c_s$
- Question: 10-100 pc scales (GMCs, molecular clouds)?

The Taurus molecular cloud

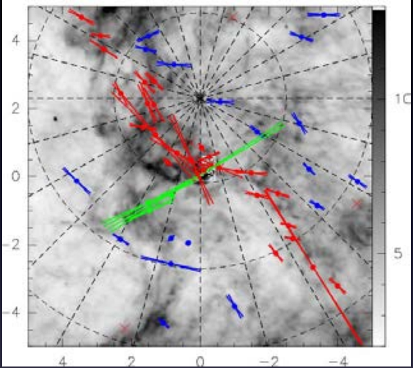


Polarization catalog of Heiles 2000 + IRAS100mic data

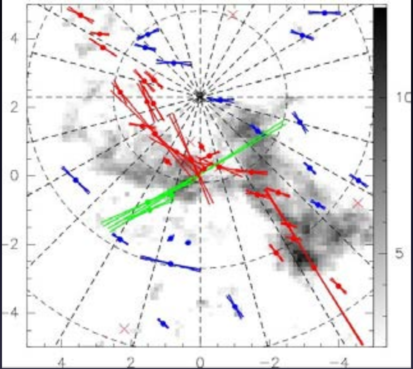
- SuperAlfvénic paradigm of star formation (MacLow & Klessen 2004)
- But, measurments of velocity anisotropy favour strong incompressible MHD (Heyer et al 2008, Goldreich & Shridar 1995)
- Absence of increase of the B-field intensity with density: favours flows along field lines rather than compression of gas (Crutcher et al 2010)
- Absence of strong shocks signatures (Hily-Blant & Falgarone 2009, Falgarone et al 2009)
- Further problems...

Observations of Magnetic Fields in the Polaris Flare

- Question: magnetic fields in a non-star forming cloud ?
- Polarization of background starlight by the dust
- Observations performed at Mont-Mégantic Observatory, Québec, with Beauty and the Beast instrument (Manset & Bastien 1995)
- In the R-band (766 nm), sensitivity $R \sim 15$mag in 2 minutes
- 3 nights in March 2010



Polar + dust



Polar + CO

Observational Results

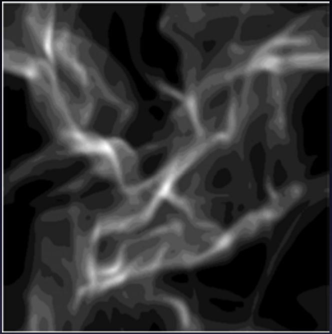
- Morphology
  - Field lines are not random on the large scales
  - A main structure running SE-NW clearly correlated with dust and gas
  - Huge variations at small scales
- Estimates of plane-of-sky B:

$$B_{\mathrm{pos}}\,(\mu G) = 6.6\sqrt{\langle n_{\mathrm{H}}\rangle}\frac{\Delta v}{\delta\theta} \approx 5\mu G$$

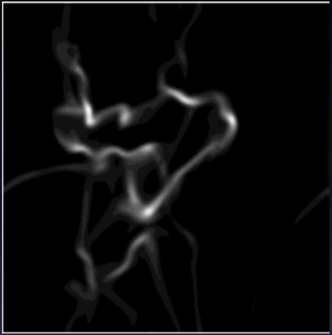
- Magnetic to dynamic pressures ratio:

$$\frac{\epsilon_{\mathrm{mag}}}{\epsilon_{\mathrm{kin}}} = \left(\frac{38}{\delta\theta}\right)^2 \approx 2.5$$

5) Sheets (from simulations)



Density field



2-D section

Padoan & Nordlund 2001

Filaments are sections of sheets formed in supersonic and superAlfvénic turbulence; cores form in those filaments

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

Falgarone, E. 1997, 170, 119

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