*Poster T25*

# Compressible MHD Turbulence in Strongly Radiating Molecular Clouds in Astrophysics*

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## ABSTRACT

Molecular clouds in astrophysics are often subjected to intense irradiation by nearby young stars. The ablation process ensues and a strong shock is driven into the cloud. In a number of cases, the radiative cooling time of the shocked matter is much shorter than the dynamical time of the cloud evolution. In such situations, possible pre-existing turbulent motions and turbulent magnetic fields can potentially contribute to the "stiffness" of the shocked material. We suggest simple models allowing quick evaluation of these effects. We conclude that the presence of a turbulent magnetic field can play a significant role, provided its amplitude is beyond some critical level, whereas the turbulent ram pressure of the unmagnetized medium can play only a relatively minor role. Implications for the dynamics of astrophysical molecular clouds are discussed.


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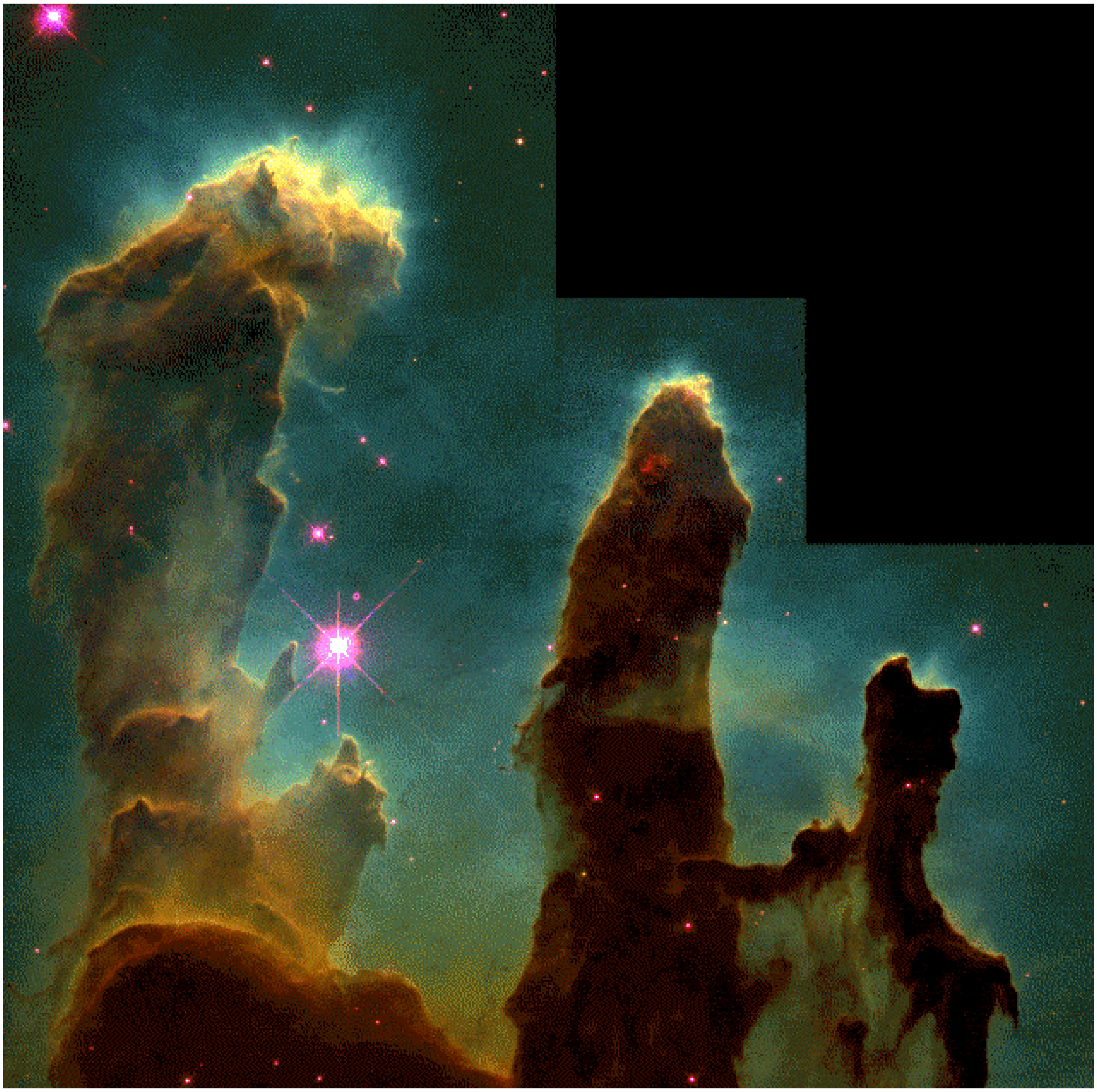
# Eagle Nebula



## OUTLINE

Formulation of the problem (supersonic turbulence decays very quickly)

Possible experiment on the temporal evolution of the trans-sonic turbulence.

MHD turbulence: can it provide necessary stiffness? – Probably, not, if radiation is fast.

“Static” MHD turbulence (random, force-free magnetic field) – Yes, it can provide necessary stiffness.

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A PROBLEM:

The molecular matter stays at a low temperature ~30 K: at higher temperatures, extremely strong heat losses begin (radiation in 1 mm range)

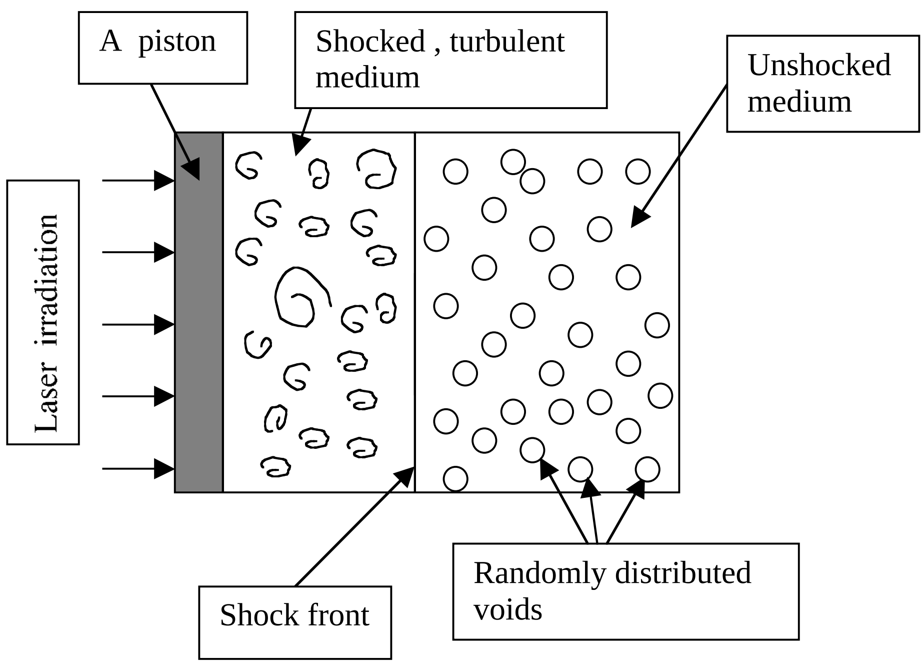
The gas pressure inferred from simple hydrodynamic arguments is much (10 to 100 times) higher than the pressure found as a product of density and temperature.

A “canonical” solution: attribute the hydrodynamic pressure to the turbulent ram pressure of a small-scale hydrodynamic turbulence. This explanation to be valid, one has to assume that the turbulence is strongly supersonic. This, in turn, would mean extremely fast dissipation (~ 1 turn-over time for characteristic vortex size), incompatible with any available energy sources.

A conclusion: hydrodynamic turbulence cannot provide required “stiffness” to molecular clouds.

# A CONCEPT OF A LASER EXPERIMENT

As it would be desirable to obtain a direct experimental information on the decay of a transonic turbulence, we suggest the following experiment:

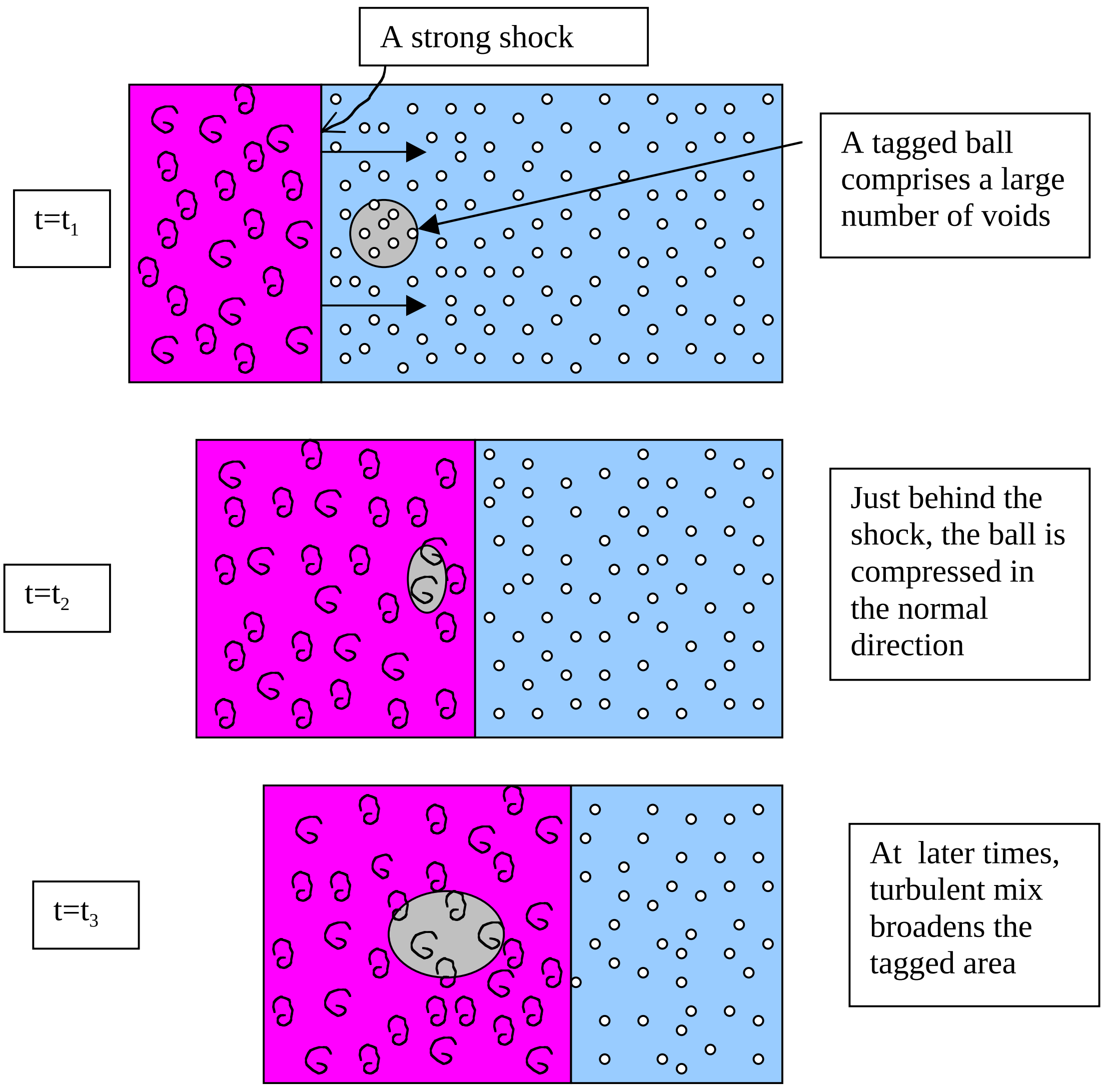



Using voids as a source of turbulent vortices is attractive because it allows one to eliminate complexities associated with mixing of different materials. Filling factor ~ 1. The shape of voids is not very important.

For a strong shock, the fluid behind the shock will be strongly turbulent, with a characteristic pulsation velocity of order of the sound velocity in the shocked material.

How to observe: add a strip seeded with a tracer; its turbulent broadening will be a measure of the turbulent diffusion.

One can introduce a spherical marker (no alignment issues). Both face-on radiography, and a side-on radiography are possible. The side-on radiography can be used to study possible anisotropy of the turbulence.




Reference experiment: compressing a "uniform" matter.

## SUSTAINING SUPERSONIC TURBULENCE

In the molecular cloud, the cooling time is typically orders of magnitude shorter than the sound transit time. Whence, even if initially the matter was hot and the turbulence was initially subsonic, very quickly the turbulent velocity becomes greater than the sound velocity. The resulting formation of shocks gives rise to a much faster decay of the turbulence than in the case of a subsonic (incompressible) turbulence.

One can try to study this process experimentally, by using the following techniques:

1) Creating conditions where the shock-heated plasma would be strongly radiating (rapidly cooling).

2) Letting the turbulent plasma to expand (e.g., in the rarefaction wave).

3) Compressing the turbulent plasma

The first approach would require reaching high temperatures of the shocked matter (may become feasible with the NIF facility)

The second (the third) approach works for the matter with a "stiff" ("soft") equation of state [effective adiabat index higher (lower) than 5/3]

MHD TURBULENCE ALSO CANNOT PROVIDE NECESSARY STIFFNESS

By MHD turbulence we mean flows with a tangled magnetic field, with the average magnetic field much less than the turbulent field.

This　　　　　　　　　Not this

Mac Low et al (1998): turbulent energy decays as

$$W_{turb} \sim t^{-\eta}, \;\; 0.85 < \eta < 1.2$$

Decay occurs within a few turn-over times for the largest-scale vortices

(M.-M. Mac Low, R.S. Klessen, A. Burkert, M.D. Smith. “Decay Timescales of MHD Turbulence in Molecular Clouds.“ In: *Interstellar turbulence*, J. Franco, A Caraminiana, Editors, Cambridge University Press, 1999. p. 256; E.C. Ostriker, J.M. Stone, C.F. Gammie. “Density, velocity, and magnetic field structure in turbulent molecular cloud models. Astropysical Journal, **546**, 980, 2001)

# EXISTING MODELS OF THE STIFFNESS OF MOLECULAR CLOUDS

| A Model | Main difficulty | Representative reference |
|---|---|---|
| Supersonic turbulence | Very high dissipation rate related to shocks | Mestel. MNRAS, 6, 161 (1965) |
| MHD turbulence | Formation of shocks parallel to the magnetic field and very fast dissipation of the turbulence | McLow et al., PRL, 80, 2754 (1998) |
| A medium composed of clumps and non-interacting shells moving at supersonic velocities | A relatively short time for collisions between dense structures (?) | Melnick et al, In "*Interstellar turbulence.*" J. Franco, A Caraminiana, Editors, Cambridge University Press, 1999, p. 148 |
| A large-scale magnetic field permeating a cloud | In most cases, the observed magnetic field strength is insufficient to provide a required stiffness | R.M. Crutcher, Ap.J. 520, 706 (1991) |

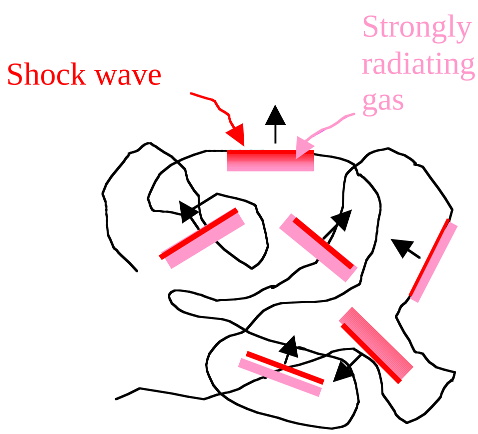
POSSIBLE LONG-LASTING TURBULENT SUPPORT: "STATIC" MHD TURBLENCE

Force-free magnetic field

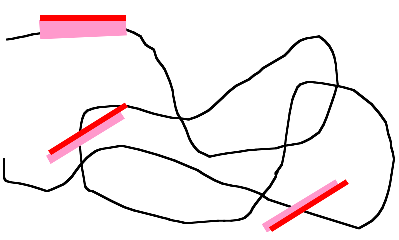
$$\nabla\times\mathbf{B}=\lambda\mathbf{B}\ (\mathbf{j}=4\pi\lambda\mathbf{B}/c)$$

Characteristic vortex size: $1/\lambda$. The parameter $\lambda$ may vary in space and time.

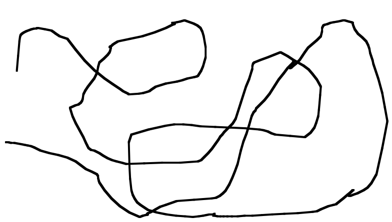
A plausible scenario leading to a formation of a force-free random magnetic field:




1) Initial (not a force-free) MHD turbulence stirs the gas, generates shocks, and transfers energy to the gas that quickly radiates it; the gas pressure remains low during this whole process;

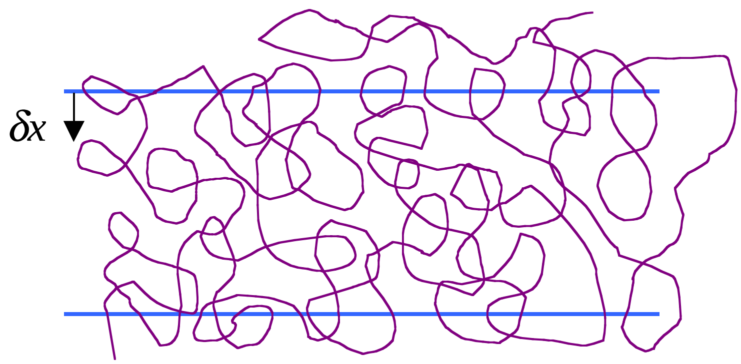


2) The system evolves in the direction of a force-free state, leading to a gradual slowing down of a stirring (and dissipation);



3) A force-free state is reached whose lifetime is determined by a very slow resistive dissipation

REACTION OF A "STATIC" TURBULENCE TO COMPRESSION




$$p = \langle p_M \rangle /3; \;\; p_M = B^2/8\pi$$

The energy density:

$$W = \langle p_M \rangle$$

The adiabat index

$$\gamma = 4/3$$

(because $p = W/3$)

A DERIVATION:

Magnetic field stress tensor

$$\pi_{\alpha\beta} = -p_M b_\alpha b_\beta + p_M (\delta_{\alpha\beta} - b_\alpha b_\beta), \ \boldsymbol{b=B/|B|}$$

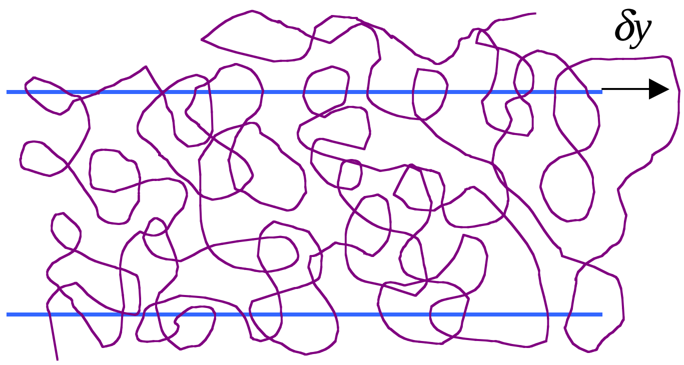
For a surface oriented perpendicularly to an axis z, the $p_{zz}$ component (the “pressure” acting on this surface) is

$$\pi_{zz} = \frac{B_x^2 + B_y^2 - B_z^2}{8\pi}$$

For isotropic turbulence,

$$p = \langle p_{zz} \rangle = \langle p_M \rangle / 3$$

REACTION OF A STATIC TURBULENCE TO SHEAR DEFORMATION




Shear stress:

$$\sigma=-(p_M/6)(d\delta y/dx)$$

There is a rheological decay of the shear stress.

DISSIPATIVE PROCESSES

Generally speaking, both compression and shear deformation trigger reconnection process that leads to some dissipation

This gives rise to appearance of the following terms in the momentum equation:

$$\sigma_{\alpha\beta} = \eta\left(\frac{\partial v_\alpha}{\partial x_\beta} + \frac{\partial v_\beta}{\partial x_\alpha} - \frac{2}{3}\delta_{\alpha\beta}\frac{\partial v_\gamma}{\partial x_\gamma}\right) + \varsigma\delta_{\alpha\beta}\frac{\partial v_\gamma}{\partial x_\gamma}$$

with

$$\varsigma \approx 3\eta = \frac{p_M}{\tau}$$

where $\tau$ is a characteristic time of the reconnection over the scale $1/\lambda$.

# SUMMARY OF THE "STATIC TURBULENCE" EFFECTS

"Static turbulence" has a very long decay time and is, therefore, an excellent candidate for a factor providing "stiffness" of molecular clouds

When a medium with initially present "static turbulence" is forced to move, the reaction is the following:

- For compressional waves, $\gamma$=4/3

- For shear waves, the shear stress is present, with a rheological decay

- Dissipative processes accompany both compressional and shear flow

A random magnetic field would not contribute a lot to a line-of sight average of polarization; small measured $\langle \mathbf{B} \rangle$ may correspond to a large $\langle B^2 \rangle^{1/2}$

# WHAT IS THE SOURCE OF THE STATIC TURBULENCE?

Initial large-scale weak magnetic field threading the cloud would be tangled in the course of fluid convection during the early stage of the cloud existence.

The magnetic pressure of this random field will be of the order of the gaseous pressure.

When the ablation pressure “turns on,” the random magnetic field is compressed and its pressure provides the necessary stiffness.

Observed line broadening in molecular transitions can be explained by two effects: radiation of the just shocked matter; the presence of non-uniform large-scale motions integrated along the line of sight.

Direct observations of the line shapes show that there exists considerable suprathermal broadening, How can this be compatible with the “static” turbulence?

An answer: locally static turbulence is compatible with supersonic velocity variation of the global flow .

A relevant quotation:

“A clear isolation of the effects of turbulent motions from observed line profiles, however, is not readily obtainable, because of the uncertainties introduced by the possible existence of large scale mass motions along the line of sight”

**G. Munch.** “Turbulence in the Interstellar Medium: a Retrospective Review,” In: “*Interstellar turbulence.*” J. Franco, A Caraminiana, Editors, Cambridge University Press, 1999. p.1.

Another possibility: the line radiation comes predominantly from the just shocked hot regions

## SUMMARY

An experiment directed towards studies of decaying compressible turbulence has been proposed

“Static” (force-free) magnetic turbulence has been suggested as a slowly-decaying agent providing a necessary stiffness to molecular clouds

Basic equations describing effects of such turbulence on macroscopic motions of matter have been formulated