Basic Physical Processes in Molecular Clouds

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Hier is wahrhaftig ein Loch im Himmel!

William Herschel (1784)

Dark nebulae are obscuring bodies nearer to us than the distant stars

E.E. Barnard (1907)

Dark nebulae are stellar birth sites

B. Bok (1946)
Molecular Gas as traced by $^{13}$CO J=1-0
The ISM in the Galaxy

Total Mass : $10^{12} \, M_\odot$ (stars, gas, dust, debris) : halo of dark matter
Stellar Mass : $10^{11} \, M_\odot$
Gas Mass : $10^{10} \, M_\odot$ : about 50% in molecular phase

Four main phases have been identified in the ISM

<table>
<thead>
<tr>
<th>Phase</th>
<th>Density (cm$^{-3}$)</th>
<th>T (K)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIM</td>
<td>0.01</td>
<td>$10^6$</td>
<td>Coronal, supernovae</td>
</tr>
<tr>
<td>WIM,WNM</td>
<td>0.3</td>
<td>$10^4$</td>
<td>HII regions, intercloud</td>
</tr>
<tr>
<td>CNM</td>
<td>30</td>
<td>$10^2$</td>
<td>diffuse</td>
</tr>
<tr>
<td>GMC</td>
<td>$\geq 100$</td>
<td>10 – 30</td>
<td>Molecular clouds</td>
</tr>
</tbody>
</table>
Molecular clouds are the densest phase of the ISM (about 50% mass)

- FUV photons are absorbed at the surface in a region of $A_v \sim 1$ : PDR (Fuente’s Talk)
- Photodissociation energy of $H_2$: 5.5 eV
- $H_2$ can survive after it has formed on dust grains, thanks to the « PDR-shield »
- Chemistry is initiated as other molecules form together with $H_2$
- Molecular clouds are not made only of molecular material!

The ISM is essentially isobaric:

$$P = 3000 \text{ K cm}^{-3}$$

Two exceptions:
HII regions and GMCs
The ISM extends over the whole galactic disk

A subregion such as: a cloud or a cloud complex is an open system

Interaction with the rest of the galaxy must be taken into account.

E.g. (multiple) GMCs are embedded in massive HI superclouds (~100 pc, grav. bound)

(Elmegreen & Elmegreen, 1987)

dynamical, thermodynamical, radiative, magnetic field
Dame (1987, 2001)

Giant Molecular Clouds traced in CO J=1-0 and J=2-1:
T=10K, n(H$_2$) $> 10^{3}$ cm$^{-3}$, size $\sim$ 50pc

Kinematics: CO bridges the GMCs, in the inter-arm regions, beyond the galactic plane
Molecular disk with scale height (≈ 250 pc)

Planck / Herschel: Molecular Clouds at High Galactic Latitude (⇒ F.X Desert)
Molecular Clouds

M51
4” (200pc)
(CO 1-0)
Associated with arms
(Egusa et al. 2011)

Taurus GMC
(Goldsmith et al. 2008)
0.03pc res
In Taurus: 50% mass in regions with Av < 2

IRDC:
Dense filamentary clouds (N ~ 10^{23} cm^{-2}) embedded in large, massive clouds;
(Perault 1996, Hennebelle 2001)
Small massive cores → MSF sites (Peretto and Fuller 2010)

M51
0.7” (30pc)
GMCs are resolved
- Interarm
- Downstream of arms

Filaments in Vela / PACS/SPIRE

M20 and WF (Lefloch 2008)
### Table 1   Physical conditions in molecule-bearing interstellar clouds (after Snow & McCall 2006, Snow & Bierbaum 2008)

<table>
<thead>
<tr>
<th>Property</th>
<th>Diffuse atomic</th>
<th>Diffuse molecular</th>
<th>Translucent</th>
<th>Dense molecular (cold cores) (hot cores)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defining characteristic</td>
<td>f^n_H2 &lt; 0.1</td>
<td>f^n_H2 &gt; 0.1</td>
<td>f^n_CO &lt; 0.9</td>
<td>f^n_CO &gt; 0.9</td>
</tr>
<tr>
<td></td>
<td>f^n_{C^+} &gt; 0.5</td>
<td></td>
<td>f^n_{C^+} &lt; 0.5</td>
<td></td>
</tr>
<tr>
<td>A_v</td>
<td>0 – ~0.2</td>
<td>~0.2–1</td>
<td>~1–5</td>
<td>~5–&gt;10</td>
</tr>
<tr>
<td>Typical n_H (cm^{-3})</td>
<td>1–100</td>
<td>100–500</td>
<td>500–5000</td>
<td>10^4–10^6</td>
</tr>
<tr>
<td>Typical T (K)</td>
<td>30–150</td>
<td>30–100</td>
<td>15–50</td>
<td>10–50</td>
</tr>
<tr>
<td>Observational</td>
<td>UV/visible absorption, H atom radio emission</td>
<td>UV/visible/IR/radio absorption</td>
<td>Visible/UV/IR/radio absorption, radio emission</td>
<td>IR absorption, radio emission</td>
</tr>
<tr>
<td>techniques</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Abbreviations: f^n_H2 is the fraction of hydrogen nuclei present as compared to H_2, i.e., f^n_H2 = 2n(H_2) / [n(H) + 2n(H_2)], where n symbolizes number density; f^n_{C^+} and f^n_CO are the fractions of carbon present in these different forms; A_v is the visual extinction parameter, a logarithmic value expressed in units of stellar magnitudes, and refers to extinction of visible wavelengths; n_H is the number density of hydrogen nuclei.
The Structure of Molecular Clouds

Galactic survey → cloud identification along the line of sight
GMC Mass distribution outside the Galactic center:

\[
dN/d \ln M = N_u \left( \frac{M_u}{M} \right)^\alpha \quad \text{(Williams and McKee, 1997)}
\]

\[
N( > M) = 105 \left[ \left( \frac{M_u}{M} \right)^\alpha - 1 \right]
\]

**Our Galaxy** : \( N_u = 63 \); \( M_u = 6 \times 10^6 \, M_\odot \); \( \alpha = 0.6 \)
- Most of the clouds are of low mass
- Most of the mass is in large clouds : > 80% is in clouds with \( M > 10^5 \, M_\odot \)

**Cutoff** : \( N_u = 63 \)
- without cutoff : \( \approx 100 \) GMCs > \( 6 \times 10^6 \, M_\odot \) : Observationally : none
- Origin unclear : formation mechanism from cooling flows ?

Other galaxies (Local Group) : similar results  (McKee & Ostriker, 2007; Blitz et al. )
GMAssociations \( M \sim 10^7 \, M_\odot \) observed at higher \( z \)
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...
Hierarchical structure: Langer et al. (1995)

From cloud scale down to Jeans wavelength, or below
Overdense regions: clumps
Star-forming clumps: clusters → grav. bound

Cores are the birthsites of stars → grav. bound
The Link with Star Formation

Thermal dust emission in ρ Oph (d=120pc) at 1.3mm

Motte (1998)
About 100 condensations identified: 59 starless with size of 15''-30''
Most of fragments are gravitationally bound

Young stars (*), protostellar and prestellar cores (X)

Cores @ same spatial scale as protostellar envelopes: progenitors of individual stars/systems.

The core mass function mimics the stellar IMF: dN/dM ∝ M^{-2.3}
Flattening and peak around 0.5 -1 M⊙ (Andre et al. 2010)

The clump mass spectrum: dN/dM ∝ M^{-1.8} (CO clumps self-grav. or not)
⇒ Why?
Dynamics of GMCs: the Larson’s relations


\[ \sigma(v) = 1.1 \ L_{\text{pc}}^{0.38} \ \text{km s}^{-1} \]

Falgarone (1997)

\[ \sigma_{\text{nth}} \propto L_{\text{pc}}^{1/3} \] (Non-SF cloud)

Supersonic motions, \( \sigma \) increases with size.
Down to 0.06 pc: HI: \( \sigma_{\text{nth}} = 3.5 \ \text{km/s} \) \( c_s \) (100K) = 0.8 km/s
\( H_2: \sigma_{\text{nth}} = 1.0 \ \text{km/s} \) \( c_s \) (10K) = 0.2 km/s
If large-scale motions (grav. collapse) then SFR \( \geq 30 \ M_\odot /\text{yr} \)!
\( \sim 10 \times \) larger than measured! (Zuckerman 1974)

Turbulence?
Heyer & Brunt (2004): this cloud-to-cloud relation extends to individual GMCs (0.03 – 30pc) \( \Rightarrow \)
Universality of turbulence in moderate-density gas

\[ \delta v = 0.9 \left( \frac{L_{\text{pc}}}{L_{\text{pc}}^0} \right)^{0.56\pm0.02} \ \text{km s}^{-1} \]
Virial Equilibrium

GMCs are in approximate mechanical equilibrium

\[ 2GM \frac{\sigma^2 L}{L} = 0.92 L \text{ (pc)}^{0.14} \]

\[ \alpha_{\text{vir}} \equiv \frac{5\sigma^2 R}{GM} \approx 1 \]

Self-gravity

\[ \sigma = 0.42 \text{ (M/M}_\odot\text{)}^{0.2} \text{ km s}^{-1} \]

Gas Column densities

Solomon (1987)

\[ <N_H> = (1.5 \pm 0.3) \times 10^{22} R_{\text{pc}}^{0.0\pm0.1} \text{ cm}^{-2} \]
Dynamics of GMCs: the Larson’s relations

These 3 relations are not independent and

\[
\alpha_{\text{vir}} = \left( \frac{5}{\pi \text{ pc}} \right) \frac{\sigma_{\text{pc}}^2}{G \Sigma} = 3.7 \left( \frac{\sigma_{\text{pc}}}{1 \text{ km s}^{-1}} \right)^2 \left( \frac{100 \, M_{\odot} \text{ pc}^{-2}}{\Sigma} \right)
\]

If turbulence is the universal support of GMCs, then

\[\Sigma \text{ is about the same for all GMCs with } \alpha_{\text{vir}} \approx 1\]

regardless of the Galactic location

Observational confirmation pending...

What about other galaxies?

Local group: dynamic range of observations (mass, size) is insufficient for clear evidence

Data are consistent with \( \sigma \alpha R^{1/2} \) with some scatter in \( \sigma_{\text{pc}} \) from galaxy to galaxy (Blitz, 2007)
Gas Dynamics in Molecular Clouds

Non-thermal supports against gravity

“Pressure” = Energy volume density

- \( P_{\text{mag}} \) Magnetic Pressure
- \( P_{\text{turb}} \) Turbulent Pressure (ram)
- \( P_{\text{CR}} \) Cosmic Rays (synchrotron radiation + collisional heating through sec. electrons; B-field coupling)

Rough Equipartition:

- \( P_{\text{mag}} \sim P_{\text{turb}} \sim P_{\text{CR}} \sim 1.0 \times 10^{-12} \text{ dyn cm}^{-2} \)
- \( 10^4 \text{ K cm}^{-3} \)

In the mid-plane: \( <B> \sim 5 \mu \text{G} \) (Zeeman: Crutcher 2010);
- \( \sigma \sim 6 \text{ km/s} \) (HI: Haud and Kalberla 2007)

The diffuse ISM gas extends up to 300pc away from the galactic plane.
Turbulence: formation of structures and fragmentation of the molecular gas; dissipation is required to permit gas condensation and star formation
Hydrodynamical instability

Shocks: dissipative mechanism: ordered motions $\rightarrow$ small-scale, thermal, motions + hydrodynamical instabilities

Ambipolar Diffusion: (de)coupling neutral matter and magnetic field, hence (anisotropic) magnetic support against gravitational collapse in cores. heating term (ions/neutral)

Radiation: Massive stars reinject energy through radiative (photoionization) processes
**Knudsen Number**: \( K = \frac{\lambda}{L} \sim (n \ (H_2)/ \ 1 \ cm^{-3})^{-1} \ (0.003/L_{pc}) \)

\( \lambda \) = mean free path (= 1/n \( \sigma \) )  
K \( \geq 1 \) : collisionless (molecular) regime  
K \( \ll 1 \) : hydrodynamical regime

In molecular clouds, the gas dynamics is governed by the Navier-Stokes equation

**Mass conservation (continuity) relation**:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,
\]

**Momentum (Navier-Stokes) Equation**:

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla P + \mathbf{f}_v + \nu \Delta \mathbf{u}
\]

**Energy equation**

**Mach number** : \( M = \frac{u}{c_s} \)

**Reynolds number** :

\[
Re = \left| (\mathbf{u} \cdot \nabla) \mathbf{u} \right| / |\nu \Delta \mathbf{u}| \sim uL / \nu
\]

Inertial vs viscosity forces

For a perfect gas : \( Re = M / K \)
For a given geometry, the flow solution depends only on (Re, M)
Two main classes of HD instabilities

**Rayleigh-Taylor** instabilities: density gradients lead to the formation of small structures → Especially important in the environment of massive stars (photoionization-driven instabilities: Capriotti et al. 1980) in HII regions

**Kelvin-Helmholz** instabilities

Detected recently in Orion (Berne, Marcelino & Cernicharo, 2010)
Turbulent flows are extremely irregular in space and time.

<table>
<thead>
<tr>
<th>Re</th>
<th>Flow Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 - 10$</td>
<td>Highly viscous, laminar (steady) motion</td>
</tr>
<tr>
<td>$10 - 10^3$</td>
<td>Laminar, (unsteady) motion $\rightarrow$ periodic oscillations</td>
</tr>
<tr>
<td>$10^3 - 10^4$</td>
<td>Transition to turbulence: chaotic oscillations</td>
</tr>
<tr>
<td>$\gtrapprox 10^4$</td>
<td>Turbulent flow</td>
</tr>
</tbody>
</table>
The gas in molecular clouds is highly turbulent...
... at levels out of reach to lab experiments.

« Turbulence is the graveyard of theories »

H.W. Liepmann
Some basic assumptions
- Incompressible flow
- Fully developed turbulence: energy injected at the largest scale L, cascades without dissipation, down to the dissipation scale $\eta$: dissipated into heat.
- Domain between L and $\eta$: inertial domain
- Space-filling cascade

The Power Spectrum
$k = 2 \pi / l$
$E(k) \, dk$: energy contained between $k$ and $k+dk$

Case of a laminar flow:
Most of the energy is contained in the large scales L
Power-spectrum: $E(k) \approx 0$ everywhere but for $k \approx 0$
The Kolmogorov Theory (K41)

**Dimensional approach**

\[ v = u - \langle u \rangle : \text{fluctuating component over distance } l \quad v_l \]

\[ t_l \sim l / v_l : \text{characteristic timescale at scale } l \]

**Reynolds number**

\[ \text{Re}_l = v_l \, l / v \quad , \quad v \text{ is the kinematic viscosity (cm}^2\text{s}^{-1}) \]

**Specific energy flux**

\[ \varepsilon_l = \rho \, v_l^2 / t_l = \rho \, l^2 / t_l^3 \quad (\text{erg s}^{-1}\text{cm}^{-3}) \]

**From } l \text{ to } \eta : \text{viscous term increases wrt bulk momentum flux.}**

**At the dissipation scale } \eta : \text{viscous terms } \sim \text{momentum flux} : \text{Re } \sim 1 = v_\eta \, \eta / v \]

**Relation 1** : \[ \varepsilon_l = \varepsilon_0 \quad \text{for } l \text{ between } L \text{ and } \eta : \quad t_l \alpha l^{2/3} \text{ or } \quad v_l \alpha l^{1/3} \]

**Relation 2** : \[ \varepsilon_0 = \varepsilon_\eta = \rho \, v_\eta^3 / \eta \quad \alpha (v / \eta)^3 / \eta \quad \Rightarrow \quad \eta \sim (v^3 / \varepsilon_0)^{1/4} \]

**Relation 3** : \[ v_L^3 / L = v_\eta^3 / \eta : \quad R_L \sim (L / \eta)^{4/3} \]
Successes of K41

Power spectrum:
3-D $E(k) \propto k^{-11/3}$  + constant $\varepsilon_1$  confirmed numerically: $2048^3$ (Kaneda et al. 2003)

Longitudinal structure functions
$v = u - \langle u \rangle$ velocity field fluctuations
$v = v_{//} + v_{\perp}$
$S_p(l) = \langle (v_{//}(x+l) - v_{//}(x))^p \rangle$ :  

Exact result: $S_3(l) = \frac{-4}{5} \varepsilon_1 l$

The 4/5 law was generalized:
$S_p(l) \propto l^{p/3}$

A large variety of methods to analyze the kinematics:
- Centroid Velocity Fluctuations methods (Miesch 1999)
- Principal Component Analysis (PCA) Heyer & Schloerb (1997)
Etc...

→ To extract from maps of molecular line emission (CO) statistical properties of the velocity field to compare with predictions from analytical theory (K41) or numerical simulations (MHD turbulence):
  → Energy density spectrum $E(k)$: transport of energy through spatial scales
  → Nature of the driving agent of turbulence
Dissipation Channel

- Rate of viscous dissipation per unit mass:
  \[
  \langle \epsilon_d \rangle = \frac{1}{2} \nu \left( \frac{\partial v_i}{\partial x_i} + \frac{\partial v_k}{\partial x_i} \right)^2
  \]

- In terms of the vorticity \( \omega = \nabla \times \mathbf{v} \):
  \[
  \langle \epsilon_d \rangle = \nu |\nabla \times \mathbf{v}|^2
  \]

- Idea: trace the vorticity... but only one velocity component in two directions \( (v_z(x, y)) \)

Dissipation timescale \( \approx 0.5 \ t_{\text{cross}} \)
2D-projected density field with $M = 10$  

*Padoan et al. (2001)*

Filaments are sections of sheets formed in SuperAlfvenic and SuperSonic turbulence $\rightarrow$ shocks
Dense cores are density maxima inside curved filaments, formed in shocks of converging flows $\rightarrow$ velocity minima, $\delta \rho \propto M^2$
Density maxima are gravitationally unstable $\rightarrow$ prestellar cores
Decay in one dynamical timescale: turbulence needs to be replenished

- In these higher-density regions, H and $\text{H}_2$ may form rapidly
  - $t_{\text{form}} = 1.5 \times 10^9 \text{yr} / (n/1 \text{cm}^{-3})$
  (Hollenbach et al. 1971)
- $\rightarrow$ either molecular clouds form slowly in low-density gas or rapidly in $\sim 10^5 \text{yr}$ in dense gas
Is the ISM turbulent?

Power-law spectra in the phases of the ISM

Electron density 3-D power in the local ISM $E(k) \propto k^{-\beta}$ and $\beta \approx 11/3$

(Armstrong 1995)

HI observations towards a cirrus cloud

CNM
Observational Evidence

At 100 pc scale

HI filaments towards the North Pole

Filaments and clumps of CO emission

Fig. 2.— Maximum antenna temperature of the $^{12}$CO $J = 1 \rightarrow 0$ transition over the velocity range 2 km s$^{-1}$ to 9 km s$^{-1}$. The antenna temperature has not been corrected for the antenna efficiency.
Elongated structures (not filaments) at
Thickness : 3 milli-pc scale (600 AU)
Length : 70 milli-pc
Strong velocity gradients : 780 km s\(^{-1}\) pc\(^{-1}\)

PdBI CO 1-0  4” res.
Falgarone (2009)
Elongated, velocity structure (no density enhancement)
Injection Scale

**Injection scale:**
Observationally: kinetic energy is at large-scale (gmc)
Upper limit on the injection scale: 100pc, (HI filaments in WIM)

*Coupling with ISM, injection efficiency are poorly known.*

**Possible mechanisms:**
Supernovae (100pc), spiral arm shocks,
Stellar winds, HII region expansion, photoionization from massive stars (10 pc)
Protostellar Outflows (0.1 – 1 pc)

$L_{\text{cloud}} \lesssim L$ (Brunt & Heyer, 2009) (comparison with MHD simulations)
→ Outflows can be important at small-scales but cannot replicate the observed large-scale fluctuations.
Specific chemistry: CH+ and SH+ detected at large abundances in diffuse gas by Herschel (Falgarone et al. 2010; Godard et al. 2009, 2012) are CH+ and SH+ tracing dissipation structures in the diffuse ISM?

\[
\text{C}^+ + \text{H}_2 \rightarrow \text{CH}^+ + \text{H}^+ + \Delta E = 4640\text{K}
\]

Local reservoir of energy >> FUV field
Turbulence is essentially proven
Its properties are not yet fully understood:
K41 has proven rather successfull but **magnetic field** is a key issue ...

Need for more **detailed simulations** and lab. experiments despite their limitations:
Freedom degree number $\alpha \operatorname{Re}^{9/4}$ for 3D incompressible turbulence: $\sim 10^5$ zones per dimension at $\operatorname{Re}=10^6$

Interferometric observations with ALMA ($0.1''$ - $0.01''$) would permit to resolve the dissipative structures of turbulence.
The magnetic field contributes to support matter against gravity, and confines CR to the Galactic disk. Both magnetic fields and CRs partake in the hydrostatic balance of the ISM and influence its stability (Boulares & Cox 1990).

Magnetic field instabilities could lead to the formation of molecular cloud complexes
→ Parker instability (Rayleigh-Taylor like) : magnetic field pressure inflate the gaseous disk → ripples in the magnetic field lines → interstellar matter slides down along lines and accumulates toward magnetic troughs → new molecular cloud complexes, triggered star formation? (Elmegreen, 1982)

The importance of magnetic field lies mainly in its role in the formation/evolution of interstellar clouds and in star formation.

Magnetic field acts on the interstellar matter through the Lorentz force: the key lies in the (collisional, momentum exchange) coupling between ions and neutrals ($x \ll 1$).

« Perfect » coupling : B-field is frozen into matter (perfect MHD)
« Imperfect » coupling : neutrals slip through B-field lines : Ambipolar Diffusion (resistive MHD)
**Magnetic Field in Orion**

350 µm polarimetry at CSO

Smooth morphology
→ B-field is strong enough to resist line twisting by turbulence.

Perpendicular to the projected major axis: OMC1/OMC3/NGC2024

→ Contraction along magnetic field lines

Except for OMC1:
B-field line orientation is the same for all cores,
Good correlation with optical measurement

Li (2009)
Li et al. (2006)

Mapping of 4 GMCs in the Galactic disk: significant correlation between the magnetic field direction with the Galactic plane. MHD simulations (Ostriker, 2001): magnetic and turbulent energies are comparable.

Optical/near-IR polarization measurements in Taurus

Smooth pattern across the cloud at ~2pc scale
Pattern varies across Taurus
(10” = 0.008pc)

Complex configuration: filaments are not parallel nor perpendicular to B-field.
**Magnetic Field in Molecular Clouds**

**Magnetic field intensity along the line of sight** is determined from Zeeman effect measurements: HI, OH ($n \sim 10^4$ cm$^{-3}$), CN ($n \sim 10^5$-6 cm$^{-3}$), C$_2$H ($n \sim 10^4$ cm$^{-3}$)

Set of diffuse cloud and molecular cloud Zeeman measurements of the los component $B_z$ plotted against $n(H) = n(HI) + 2n(H_2)$.

**Statistical analysis (Crutcher et al. 2010)**
- $n > 300$ cm$^{-3}$ : $B \propto n^{k(\approx 2/3)}$ and $k > 0.6$
- $n < 300$ cm$^{-3}$ : $B$ *cst*

*(consistent with MHD simulations: Hennebelle et al. 2008)*

**Two extreme cases**:
- $B$ « weak »: cloud collapse unaffected: $B \propto n^{2/3}$ (*Mestel, 1956*)
- $B$ « strong »: cloud collapse *along* field lines

**Magnetic field intensity in the plane of the sky** is determined from linear dust polarization measurements using the Chandrasekhar-Fermi method

$$B_{pos} \approx Q \sqrt{4\pi \rho \frac{\Delta v_{los}}{\Delta \phi}}$$

$\Delta v_{los}$ is the 1d velocity dispersion (los)
$\Delta \phi$ dispersion of the polarization angle
$Q$ is a geometrical parameter: calibrated from MHD simulations: $Q \approx 0.5$ (*Ostriker, 2001*)
Magnetic field is independent of n at low density:
→ B is strong enough that cloud formation proceeds primarily by matter accumulation along magnetic field lines (Polaris)
→ Breaking point: self-gravity comes into play?

In dense clouds: \( B = 0 - B_{\text{max}} \alpha n^{2/3} \)
→ Gravitational collapse is not always driven by magnetic field
→ Many clouds have small magnetic fields
→ Clouds with strong magnetic field are (slightly) magnetically (super)critical
Molecular clouds are usually weakly ionized

\[ \rightarrow \text{Determination of the ionization fraction from } \text{HCO}^+ / \text{DCO}^+ \ (\text{Guelin, 1977}): x_e = 10^{-5} - 10^{-8} \]

Electromagnetic force acting on the ions

- \( n_i = n_e, n_n \): density of ions, electrons and neutrals (\( \text{cm}^{-3} \))
- \( n_i = x_e n_n \) \( \Rightarrow \rho_i \approx x_e \rho_n \) since \( m_i \approx m_n \)
- Current: \( \vec{j} = \sum_i n_i q_i \vec{v}_i \)
- Ampère’s equation: \( \nabla \times \text{B} = \mu_0 \vec{j} \)

Lorentz Force acting on the ions

\[ \vec{f}_L = \vec{j} \times \text{B} = \frac{1}{\mu_0} (\nabla \times \text{B}) \times \text{B} \]
Momentum exchange in a collision neutral/ions

Timescale between two collisions of a neutral with ions

\[ \tau_{i \rightarrow n} = [n_i \langle v_{in} \sigma(v_{in}) \rangle]^{-1} \]

Momentum received by the neutral in an elastic interaction

\[ \Delta \vec{p}_{i \rightarrow n} = \frac{m_i m_n}{m_i + m_n} (\vec{v}_i - \vec{v}_n) \]

Drag Force exerted by (unit of volume of) ions on neutrals

\[
\vec{f}_{i \rightarrow n} = \frac{d \vec{p}_{i \rightarrow n}}{dt} = n_n \frac{\Delta \vec{p}_{i \rightarrow n}}{\tau_{i \rightarrow n}} = n_n \frac{m_i m_n}{m_i + m_n} (\vec{v}_i - \vec{v}_n) n_i \langle v_{in} \sigma(v_{in}) \rangle
\]

Force acting on the ions

\[
\vec{f}_c = -\vec{f}_{i \rightarrow n} = -\rho_n \rho_i \gamma (\vec{v}_i - \vec{v}_n)
\]

\[ \rho_\alpha = n_\alpha m_\alpha \]

and the friction coefficient

\[ \gamma = \frac{\langle v_{in} \sigma(v_{in}) \rangle}{m_i + m_n} \]

\[ m_i \approx m_n \]

\[ \gamma = \frac{n_i \langle v_{in} \sigma(v_{in}) \rangle}{2 \rho_i} \approx (2 \rho_i \tau_{i \rightarrow n})^{-1} \]
Ambipolar Diffusion

Drift velocity

Ions are at equilibrium

\[ \vec{f}_L + \vec{f}_c = 0 \]

\[ \vec{v}_d = \vec{v}_i - \vec{v}_n = \frac{1}{\mu_0 \rho_i \rho_n \gamma} (\vec{\nabla} \times \vec{B}) \times \vec{B} \]

Magnetic field evolution

Magnetic flux equation

\[ \frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \times (\vec{B} \times \vec{v}_i) = 0 \]

\[ \partial_t \vec{B} + \vec{\nabla} \times (\vec{B} \times \vec{v}_n) = \vec{\nabla} \times \left( \frac{1}{\mu_0 \rho_i \rho_n \gamma} \vec{B} \times [\vec{B} \times (\vec{\nabla} \times \vec{B})] \right) \]
Weakly ionized medium: $x = 10^{-5} n_n^{1/2} \rho_i \approx 2 \times 10^{-17}$

- $\langle \sigma v_{i-n} \rangle \approx 2 \times 10^{-9}$ cm$^3$ s$^{-1}$, $\gamma \approx 3 \times 10^{14}$ cm$^3$ g$^{-1}$ s$^{-1}$
- $n_n = \rho_n/m_n = 10^4$ cm$^{-3}$
- $v_A = 0.4$ km s$^{-1} (n_n/10^4$ cm$^{-3})^{-1/2} (B/30\mu G)$

Drift Velocity

\[
\frac{1}{\mu_0 \rho_i \rho_n \gamma} (\vec{V} \times \vec{B}) \times \vec{B}
\]

- $v_L = \gamma \rho_i L \approx 3$ km s$^{-1} (L/0.1$ pc)
- $v_d \sim \frac{B^2}{\mu_0 \rho_i \rho_n \gamma L} \approx \frac{v_A^2}{v_L}$
- $v_d \approx 0.05$ km s$^{-1}$

Ambipolar Diffusion Timescale

$\tau_{AD} \approx 3 \times 10^6 (n(H_2)/10^4$ cm$^{-3})^{3/2} (B/30\mu G)^{-2} (L/0.1$ pc)$^2$ yr

Slow process in PSCs, Fast in shock regions.

Heating rate

$\Gamma_{AD} = |\vec{F}_c \cdot \vec{v}_d| = \gamma \rho_i \rho_n v_d^2 \approx 10^{-24}$ erg s$^{-1}$ cm$^{-3}$
Large-scale Feedback

Outflows in a typical SFR: Orion

Multiplicity
Parsec-scale ejections

Outflows in NGC1333
Expanding Cavities

Lefloch et al. (1998)

Stanke et al. 2002
Shocks are dynamically important: $\Delta v \gg c_s$

CO 2-1 in Taurus at the IRAM 30m
Shocks

Two regimes of shocks (Draine, 1980)

\[
\begin{align*}
J &= \text{J-type (HD)} \\
B=100\mu\text{G} &= \text{C-type (MHD)}
\end{align*}
\]

Two regimes defined by B

- Structure
- Timescales
- Compression, Tmax
- Thickness

Transition from J to C shock

\[
V_s > V_A = \frac{B}{(4\pi \rho)^{1/2}}
\]

\[
V_s > V_{\text{diss}}(\text{H}_2)
\]

Cabrit et al. 2004

Flower and Pineau des Forets (2010)
H₂, CO and H₂O are the main cooling agents in MHD shocks. OH and OI can also contribute (see e.g. Benedettini et al. 2012, Nisini et al. 2010).

H₂O and CO can reach $T \geq 10^3$ K in a C-type shock.

H₂O and CO reform at about 300K in a J-type shock.
Observational signatures

Shock signatures are rather specific
Non Steady-State Shock Models

Steady-State MHD shock models usually don’t work

Non-stationary CJ shock:
a J-shock precedued by a magnetic precursor.

The MHD component gradually overcomes the HD discontinuity (Chieze, 1998; Gusdorf et al. 2008)

Figure 1. Thermal profile of the neutral fluid, as computed for a C1-type shock wave of speed $v_t = 20\text{ km s}^{-1}$, propagating into molecular gas of density $n_e = 2n(H) \equiv 10^4 \text{ cm}^{-3}$, with an initial transverse magnetic field strength $B = 100 \mu\text{G}$. The independent variable in this figure is the flow time of the ionized fluid, $t$. The dynamical age was varied in the range $500 \leq t \leq 5000\text{ yr}$. The corresponding C1-type model, i.e. the steady-state solution, attained by $t = 10000\text{ yr}$, is shown for comparison purposes. As the shock wave ages, the J-discontinuity moves to the right, becoming progressively weaker as equilibrium is approached.
Evolution of molecular abundances in a MHD shock: influence of sputtering and high-T temperatures.

The Spectral Line Distribution can be used to characterize the shock parameters.
Observational constraints:
Lines of H$_2$ (mid-IR: ISO, Spitzer, JWST, SPICA ?)
High-J CO, H$_2$O : HSO

Typical MHD shock thickness $\sim 4 \times 10^{16}$ cm = 15” at 160pc within reach to IRAM 30m
(with the right tracer!)
Best done with PdBI /NOEMA and ALMA

Observations and modelling are closely coupled:
State of the art models can account (at best) for CO, H$_2$ and SiO simultaneously…
(Gusdorf et al. 2008; Flower & Pineau des Forets 2012)
The radiation field of a young massive star influences the surrounding cloud gas and dust

\[ \text{Ly-}c \text{ photons: Ionization front.} \]

\[ \text{Ts} \sim 10^4 \text{ K} \]

Ionized surface layers expand back into the HII region

\[ \Phi = n_i c_i + \eta \alpha n_i^2 R \]

Kahn (1956), Bertoldi (1989)
The radiation field of a high-mass star influences the surrounding gas and dust → Ly-\( \alpha \) photons: Ionization front.

Radiatively-Driven Implosion

Ionized surface layers expand back into the HII region; CG7S

Shock Front propagate into the molecular clump, photoevaporated

Mass-Loss

h \nu

Photoionization shapes the surface of HII regions and can trigger Star Formation
The physics of Molecular Clouds are extremely rich... though not fully understood...

They have strong implications on the chemical evolution of gas and dust. There is actually a strongly between chemistry and dynamics...

More of these processes will be addressed during the Talk on Chemistry in protostellar environments...
It is a pleasure to thank Pierre Hily-Blant and Cecilia Ceccarelli (IPAG) for their help and our discussions in the preparation of this brief lecture on physical processes in Molecular Clouds.
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