GLOBAL MODELS OF ISM

Field, Goldsmith, & Habing (1969)
McKee & Ostriker (1977)
Cox & Smith (1974)

Global model → quasi-steady state that accomodates observed properties

Key observation: ISM is multi-phase
- hot (ionized)
- warm (ionized, partly ionized)
- cold (atomic, molecular)

First important global model is FGH (1969), explaining the two basic components (hot + cold). It enunciates the key principle of pressure balance.

If some part is not in pressure balance, it will adjust itself to be: if P is too low, it will be forced to contract by the surrounding medium. If P is to high, it will expand until equilibrium is reached.

Consider thermal equilibrium:

$$n\Gamma = \text{heating rate / volume}$$
$$n^2\Lambda = \text{cooling rate / volume}$$

$\Lambda = f(T)$ only for low densities, where the de-excitation is radiative

$\Rightarrow \mathcal{L} \triangleq \Lambda - \Gamma/n$, $\mathcal{L} \propto$ net cooling rate / mass

In equilibrium, $\mathcal{L} = 0$.

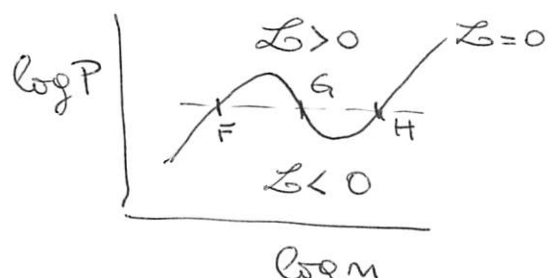
Take a blob, imagine its temperature fluctuates but it remains in pressure equilibrium.

$$\Rightarrow \quad \delta P = 0 \quad , \quad \frac{\delta n}{n} = -\frac{\delta T}{T} \quad \Rightarrow$$

$$\text{If} \quad \left.\frac{\delta \mathcal{L}}{\delta T}\right|_p < 0$$ ($T\uparrow$ leads to $\mathcal{L}\downarrow$, decrease in net cooling)

$\Rightarrow$ equilibrium is unstable: higher $T \rightarrow$ lower $\mathcal{L} \rightarrow$ higher T

For moderate density and temp. the curve for $\mathcal{L} = 0$ looks like

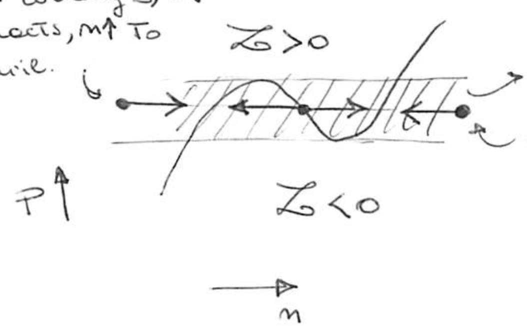


($P = nkT$)

F, H ← stable ~~equilib~~

G ← unstable

Positive net cooling $\Rightarrow T\downarrow$
$\Rightarrow$ blob contracts, $n\uparrow$ to reach equil.



2-phase region

$T\uparrow$
negative net cooling $\Rightarrow$ blob expands ($n\downarrow$) to reach ~~equil~~ P equilibrium

Why does this happen?

- $\Lambda\uparrow$ rapidly with $T\uparrow$ for low T, ($T \lesssim 100$ K) because of CII cooling
- $\Lambda\uparrow$ rapidly with $T\uparrow$ for high T, ($T \gtrsim 800$ K) because of Lyα cooling

Thus for heating by CR (FGH 69), with Γ indep. of T, or by photoelectric effect (e.g. Wolfire et al 95), with weak Γ of T,

we have the two-phase region

For there to be 2 stable phases, <u>we need an unstable phase in between</u>

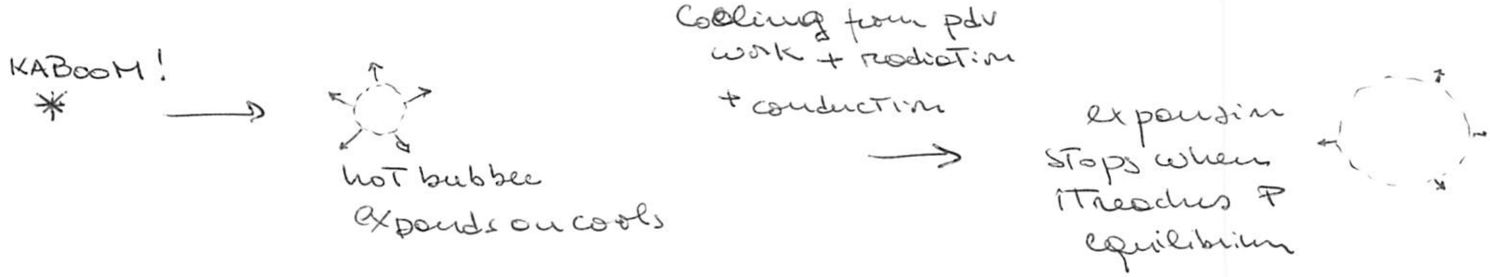
This is a simplification, since we also have the hot medium from SN and OB association winds.
⇒ driven by shocks. Post shock temperatures are

$$T = 1.4\times10^{5}\left(\frac{V_s}{100\ \mathrm{km\,s^{-1}}}\right)^{2}$$, shock speed V_s

⇒ shock of a few 100 km s^{-1} easily heat the gas to 10^6 K.

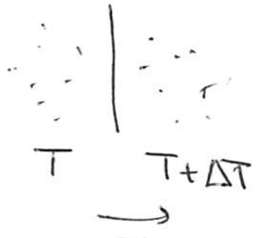
SN expansion details → discussed later

Big picture →



Key physical process in hot medium: conduction

⇒ heat flux $-K\nabla T$, conductivity $K(T)$. Heat moves down gradient in T, transferred by electrons.
$K \propto T^{5/2}$, highly temperature sensitive. Only important for hot medium. Why?



Energy flux in $\vec{x}$: $n\cdot(\delta v_x)\cdot kT\big|_x - n(\delta v_x)\,kT\big|_{x+\Delta x}$

$$\sim \Delta x\cdot\frac{\partial}{\partial x}\left(n\, v_x\, kT\right) \triangleq -K\frac{\partial T}{\partial x}$$

$$\Rightarrow K \sim \Delta x\cdot n\,\delta v_x\, k$$

Δx = mean free path $= \frac{1}{n\sigma}$ $\quad \sigma$ = cross section $= b_{eff}^2$ for electron scattering

Strong energy exchange for $\frac{e^2}{b_{eff}} = kT$ $\Rightarrow \frac{1}{b_{eff}^2} = \left(\frac{kT}{e^2}\right)^2$

δv_x = mean random velocity in $\vec{x}$ dir $\sim C_s \sim \left(\frac{kT}{m_e}\right)^{1/2}$

$$\Rightarrow K \sim \frac{1}{\cancel{n} b_{eff}^2} \cancel{n} C_s k \sim \frac{k}{b_{eff}^2}\left(\frac{kT}{m_e}\right)^{1/2} \sim \frac{k(kT)^2(kT)^{1/2}}{m_e^{1/2} e^4} \sim k^{7/2}\frac{T^{5/2}}{m_e^{1/2} e^4}$$

Quantitatively: $K = 5.6\times10^{-7}\,\phi_c\,T^{5/2}$ erg s^{-1} K^{-1} cm^{-1}

accounts for effects of Turbulence, magnetic field, etc — fudge factor

Energy equation is $\quad \frac{\partial e}{\partial t} + \nabla\cdot\left[(e+P)\vec{v} - K\nabla T\right] = -n^2\mathcal{L}$

Energy / Volume $\qquad \mathcal{L} = \Lambda - \Gamma/n$

Conduction Term is $\sim \frac{KT}{L^2}$

radiation is $n^2\mathcal{L}$

Conduction > radiation if $\frac{KT}{L^2} > n^2\mathcal{L}$ $\Leftarrow$

"Field Length" $\lambda_F \triangleq \left(\frac{KT}{n^2\mathcal{L}}\right)^{1/2} > L$ $\Leftarrow$ $\Big\}$ equivalent

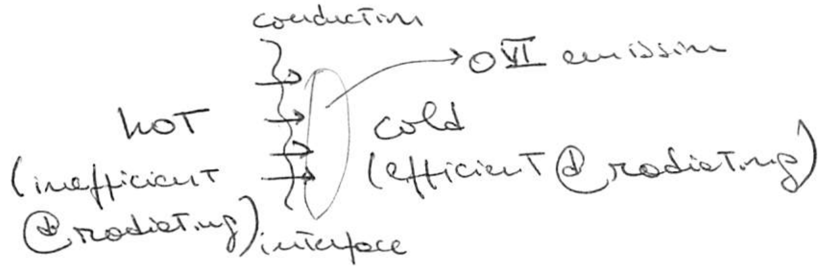
Ex: @ $T\sim10^6$ K $\quad n^2\mathcal{L}\sim10^{-22} n^2$ erg cm^{-3}

$$\lambda_F \simeq \left(\frac{10^{-6}\,T^{7/2}\phi_c}{10^{-22}\,n^2}\right)^{1/2} \Rightarrow \frac{\phi_c^{1/2}}{n}\cdot 3.1\times10^{18} \approx \lambda_F$$

$$\Rightarrow \lambda_F \sim \frac{\phi_c^{1/2}}{n}\ \text{pc}$$

For sizes $< \lambda_F$ conduction dominates radiation, and clouds are evaporated. This limits the thermal instab. of hot medium

Initial expansion is adiabatic (allowing for conductive cooling). Afterwards radiation becomes important.



McKee & Ostriker (1977) is highly detailed. Predicts mean pressure $P \sim 3600\ cm^{-3}\ K$, consistent w/ observed value and within range for which 2-phases are possible

Basic uncertainty: how important conduction is, because of uncertainties in $\vec{B}$ geometry (hence ϕ_c)

Tangled field → poor conduction (low ϕ_c) → SNR expands ~~more freely~~ for longer (poor radiative cooling).

This has consequences for filling fraction of hot gas

Other things that affect FF: Type II SN go off in concentrated regions, blow off of hot gas in chimneys.

External galaxies have low filling fractions of hot gas. Locally (local bubble) it is important.

The argument in the past has frequently been a process of elimination: one observed certain phenomena, and one investigated what part of the phenomena could be explained; then the unexplained part was taken to show the effects of the magnetic field. It is clear in this case that, the larger one's ignorance, the stronger the magnetic field.

LODEWIJK WOLTJER, 1966

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Lodewijk Woltjer, 1966

MAGNETIC FIELDS

"The larger one's ignorance, the stronger the magnetic field"

Lodewijk Woltjer 1966

IAU Symp. 31 "Radio Astron. & the Galactic System"

1

In neutral gas → Zeeman Splitting

Needs transitions with magnetic splitting of energy levels (magnetic moment of atom/molecule)

- 21 cm line → absorption against bg / → emission

- OH molecule

Zeeman yields $\langle B_{\parallel} \rangle$ ($\parallel$ to l.o.s., i.e., along los)

~ Tens of μG in dense clouds

(Heiles & Crutcher 2005 review)

In HI, $\langle B_{\parallel} \rangle = 5\text{-}20\,\mu G$ with many $\langle B_{\parallel} \rangle < 5\,\mu G$

From absorption, $|B_{TOT}| = 6 \pm 1.8\,\mu G$

emission, $|B_{TOT}| \sim 10\,\mu G$ (mostly sheets where field is likely enhanced)

Polarization measurements (eg, dust) give the direction of $B_{\perp}$. The magnitude can be estimated using the Chandrasekhar - Fermi method (1953)

$$B \approx \sqrt{4\pi\rho}\ \frac{\sigma(v_{\perp})}{\sigma(\phi)}$$

$\sigma(v_{\perp})$ ← velocity dispersion

$\sigma(\phi)$ ← measured dispersion of angles in the sky

ρ ↑ mass density

This is for $\phi \ll 1$

To see shortcomings, etc., see discussion in Houde (2004) and references therein

On larger scales, the $\vec{B}$ can be measured in the ionized ISM using pulsar rotation measure + dispersion measure (in other galaxies, background QSOs may be used) ②

$$\phi = RM \cdot \lambda^2$$

$$RM = 0.810 \int_0^D n_e B_{\parallel} dl \qquad [n_e] = cm^{-3} \quad [B_{\parallel}] = \mu G \quad [RM] = rad\,m^{-2}$$

$$[D] = pc$$

$$DM = \int_0^D n_e\, dl \qquad [DM] = pc\,cm^{-3}$$

$$\Rightarrow \langle B_{\parallel} \rangle = \frac{RM}{DM} = 1.232 \frac{RM}{DM} \qquad \text{(e.g. Han et al. 2006)}$$

From studies of a sample of pulsars in a range of directions and distances, we can model orientation and magnitude of $\vec{B}$ in the MW. (e.g., Rand & Lyne 1994, MNRAS 268, 497)

1) Field is mostly along the arm ~ 1.4 μG ∥ to arm, 1.8 μG total ~~in general~~

2) $\langle B_z \rangle = -0.4\ \mu G$ (toward NGP)

3) Field reverses @ 0.3 kpc inside solar circle

4) Probable 2nd and 3rd reversals @ 5 kpc and 3 kpc from center ⇒ ½ wavelength is ~ 3 kpc

Using dispersion in plane of sky, total field ~ 6 μG (B uniform ~ 4 μG) (Beck et al. 2004)

Mention Goldreich-Kylafis effect.

COSMIC RAYS

γ Lorentz factor

$N(\gamma)\,d\gamma$ = no. of particles within γ, $\gamma + d\gamma$

$$N(\gamma) \propto \begin{cases} \gamma^{-2.5} & \gamma < 10^6 \\ \gamma^{-3.7} & 10^6 < \gamma < 10^4 \end{cases} \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\rho_E = 3.9 \times 10^{-12}\ \text{erg cm}^{-3} \sim 2\ \text{eV cm}^{-3}$$

Similar to energy of B field ($\rho_B \sim 1.4 \times 10^{-12}$ erg cm^{-3}), starlight, and CMB (coincidentally)

Most of the energy density is in the low γ CRs

Responsible for heating/ionization of CNM, although they may not be enough (Turbulence?)