The Global ISM

References:

Draine ch 30 (2 phase medium) & ch 29 (HI properties)
Draine 39.4 (3 phase medium)
Also
- Dopita ch 14
- Tielens ch 8
- Spitzer

Gas Phases

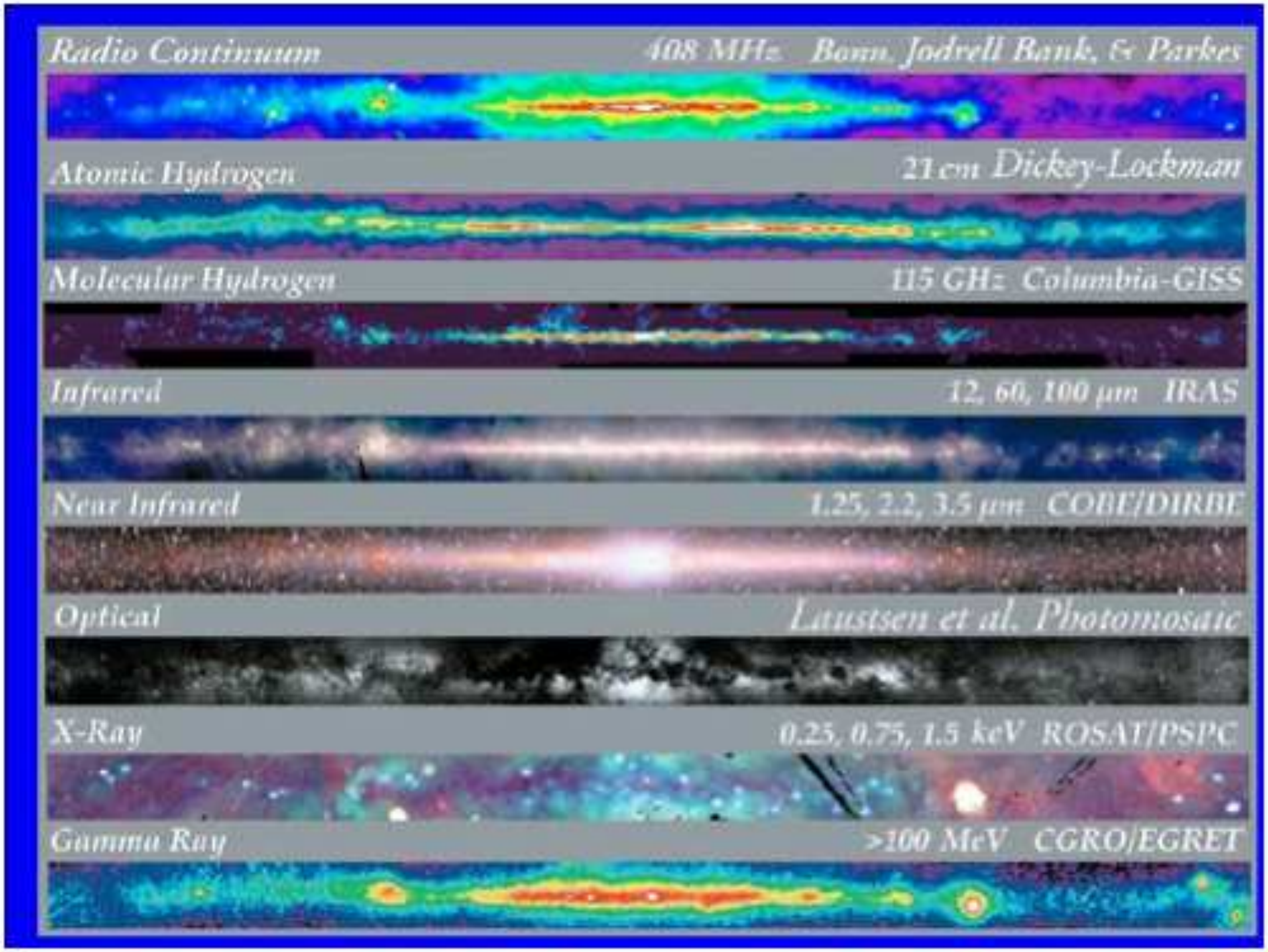
- Most of the Milky Way ISM is neutral gas.
  - What temperature do we expect HI to have?
  - We will learn that more than one equilibrium temperature is possible.
  - This model is known as the 2-phase ISM.
- Observed Components of the ISM
- ISM is a dynamic place.
  - Shocks heat, churn, and compress gas.
  - Dense clouds give birth to stars.
  - Stars heat the gas and generate shocks.
  - The model that includes this hot gas is known as the 3-phase model of the ISM.

Components of the ISM

Table 1: Components of the interstellar medium[1]

Component	Fractional Volume	Scale Height (pc)	Temperature (K)	Density (atoms/cm³)	State of hydrogen	Primary observational techniques
Molecular clouds	< 1%	70	10—20	10^2—10^6	molecular	Radio and infrared molecular emission and absorption lines
Cold Neutral Medium (CNM)	1—5%	100—300	50—100	20—50	neutral atomic	H I 21 cm line absorption
Warm Neutral Medium (WNM)	10—20%	300—400	6000—10000	0.2—0.5	neutral atomic	H I 21 cm line emission
Warm Ionized Medium (WIM)	20—50%	1000	8000	0.2—0.5	ionized	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2—10^4	ionized	Hα emission and pulsar dispersion
Coronal gas Hot Ionized Medium (HIM)	30—70%	1000—3000	10^6—10^7	10^{-4}—10^{-2}	ionized (metals also highly ionized)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

- Note P/k ~ 3000 K cm-3 for CNM, WNM, WIM, and HIM
- This pressure is simply a boundary condition for self-gravitating clouds; and most self-gravitating clouds turn out to be molecular clouds. Some diffuse molecular clouds may not be self-gravitating.
- HII regions are over-pressured. They are small and expanding.


Radio Continuum
408 MHz Bonn, Jodrell Bank, & Parkes
Atomic Hydrogen
21 cm Dickey-Lockman
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray
>100 MeV CGRO/EGRET

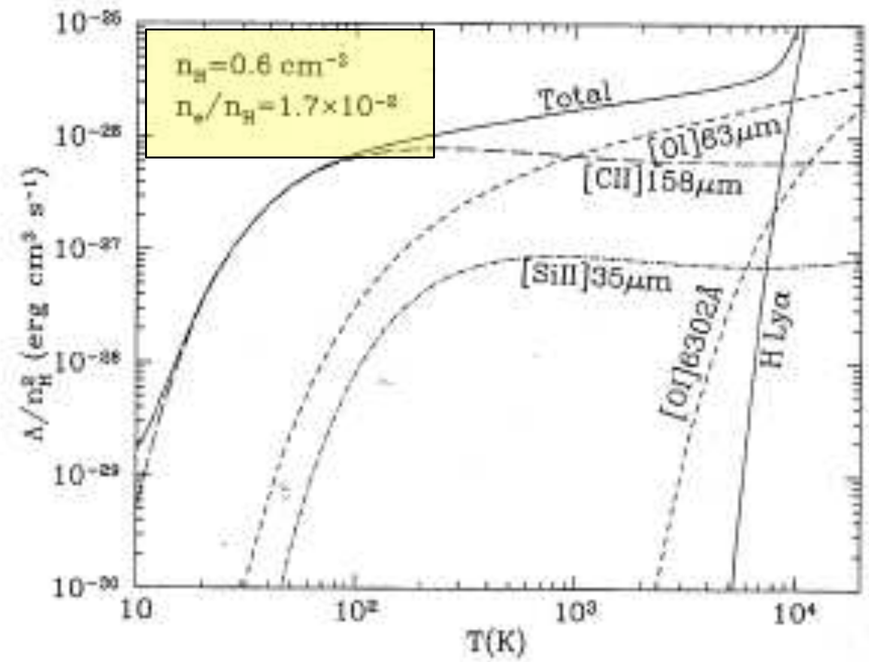
Phases of the Interstellar Medium

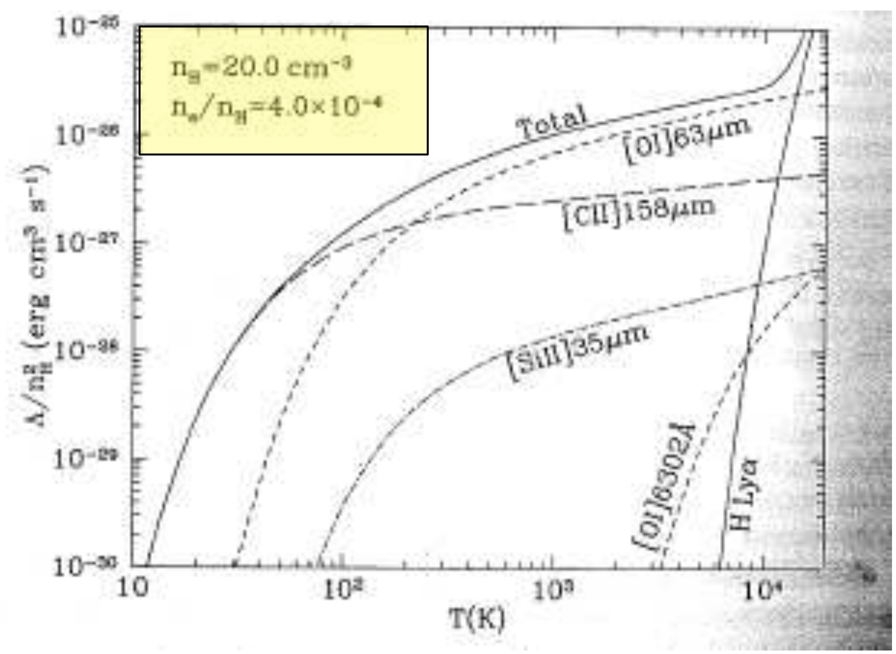
- Gas **phases** characterized by different temperatures, densities, and ionization fractions
- A stability analysis explains the coexistence of multiple phases
- In general, a stable phase reflects the onset of a new cooling mechanism or the decline of a heating source
  - Cold HI clouds and the warm intercloud medium result from the increased importance of [CII] cooling at higher densities and Lya and [OI] 6300 cooling at higher T.
  - The hot phase reflects the recent input of supernova energy
  - Cold molecular clouds result from the increased cooling due to rotational transitions in molecules

Heating and Cooling of the Neutral, Atomic Medium

- At low temperature in diffuse clouds, the dominant cooling process is ______ .
- Possible heating sources
  - **Far-UV photons** (EUV photons absorbed in HII regions)
  - Cosmic rays
  - Turbulence (supernova, galactic differential rotation, protostellar outflows)

Cooling Rate in Neutral HI Gas





For T < 104 K, the cooling is dominated by ________ .
HI Lya becomes an important coolant at T > ______ .

The Two-Phase Medium

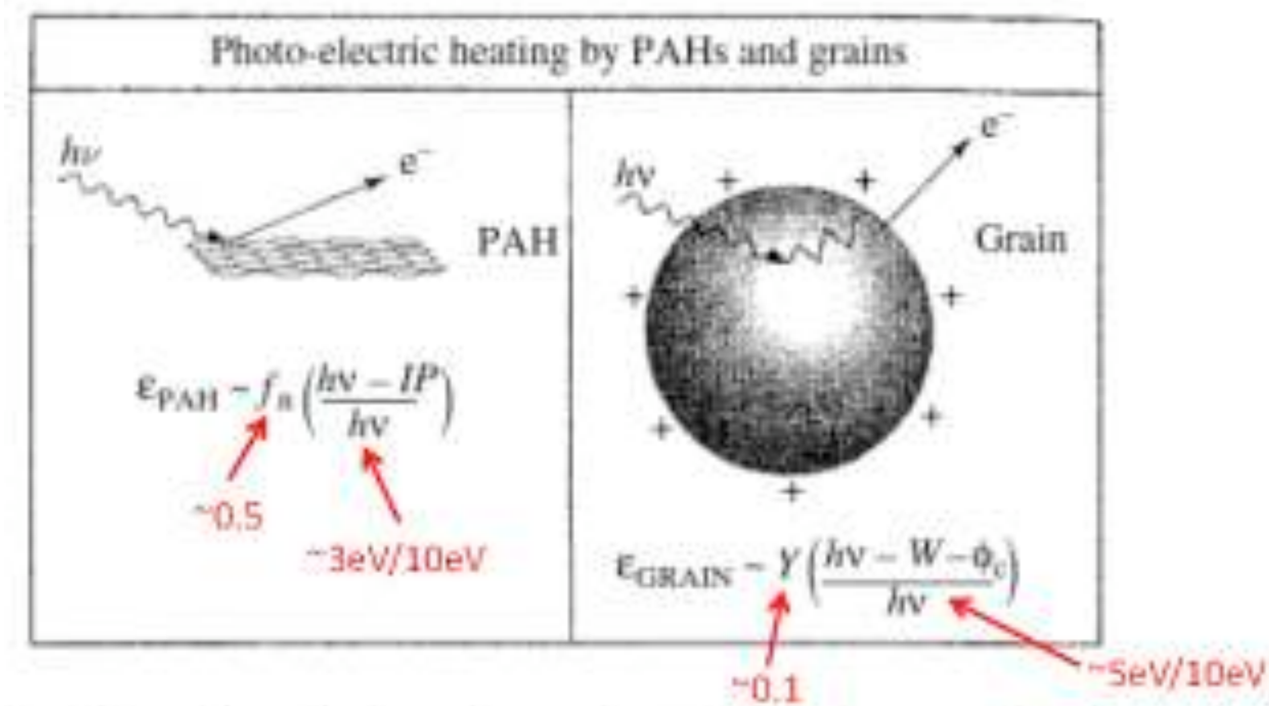
- Field 1965 ApJ 142, 531
- Field, Goldsmith, & Habing 1969 ApJ 155, L149
- Cosmic-ray ionization was assumed to be the dominant heating agent.
- To achieve a temperature of 80 K, typical of CNM clouds, the CR ionization rate has to be 15 times larger than that favored by more recent measurements.
  - Dishoeck & Black 1986
- Nonetheless, because the heating due to CRs has a simple form independent of density and temperature, we use this old model for illustration
- [BB]

Modern Two-Phase Medium

- If cosmic ray heating comes up short, then what process dominate the heating of the neutral medium?
- One might guess ionization of C. But it turns out there's another process that's about 1000 times more efficient.
- The heating of diffuse, atomic clouds is dominated by the photo-electric effect on large molecules and small dust grains

Photoelectric Heating

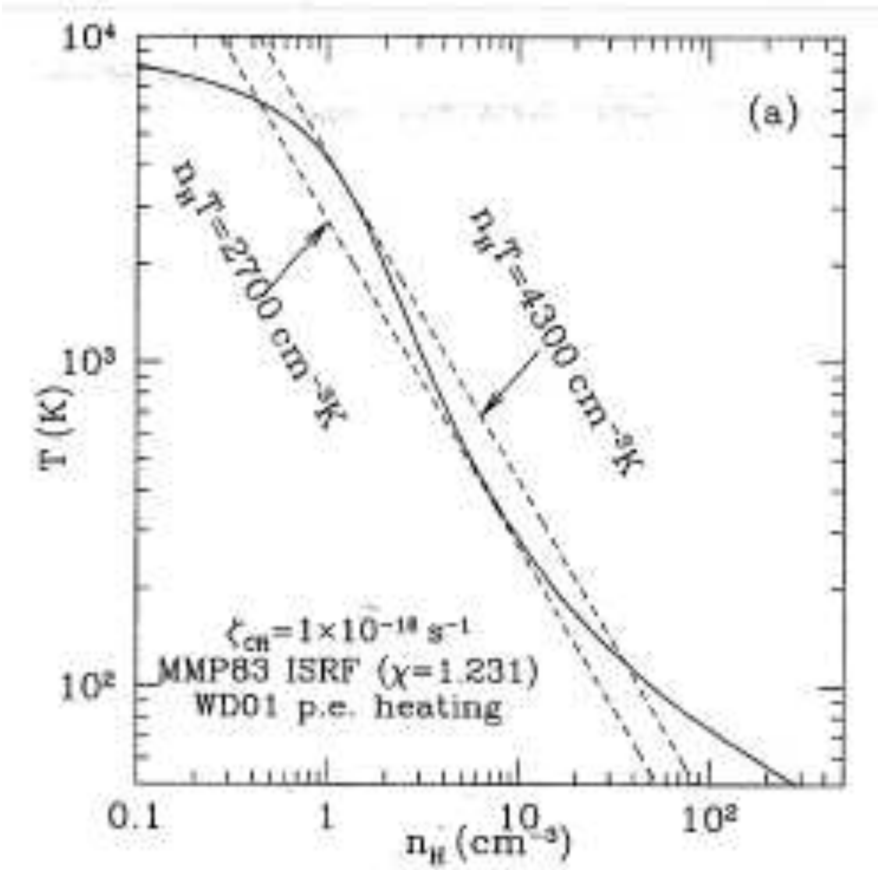
- FUV photons absorbed by grain; electrons with a few eV diffuse through the grain and lose energy through collisions; if the overcome the work function of the grain, then they are injected into the gas

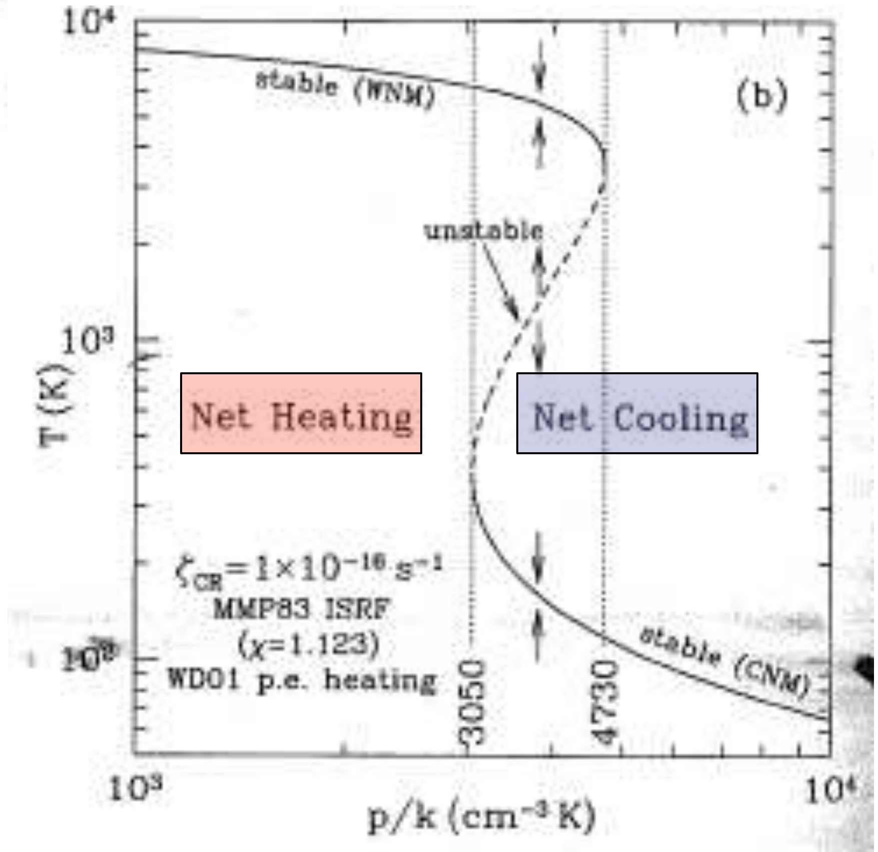


Photoelectric Heating

- Small grains, a.ka. Large molecules, are the most effective source of photo-electric heating
  - Dominate the FUV absorption
  - Photo-electons escape most easily from planar PAH's
- Heating is also more effective when the grains have a low charge. [See Tielens fig 3.4]
- The grain charge is a balance between photo-ionization and e- recombination.
- For small charge, the heating $n\Gamma$ grows with G_0n
- For large charge, the heating $n\Gamma$ grows with nn_e through the recombination rate

Steady-state Temperature





Three-phase Model

- McKee & Ostriker 1977
- Supernova pump energy into the the ISM
- The very hot bubbles are not really a stable phase; recall the $T^{1/2}$ dependence of free-free cooling rate
- The long cooling time, however, means that a significant volume of the ISM may be filled with Hot Ionized (Intercloud) Medium.
  - For $T > 10^6$ K; low density gas takes over 1 Myr to cool
- Estimated porosity Q [BB]

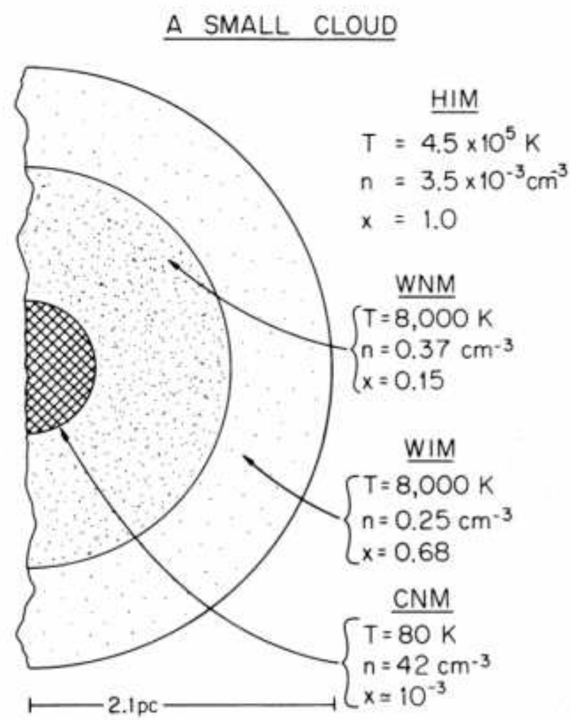


FIG. 1

Three-phase Model

- Predicts that supernova remnants overlap, thereby forming a volume filling HIM, at a pressure P/k ~ 6000 cm^{-3} K.
  - Remarkable agreement with the observed thermal pressure.
- Fails to predict a substantial warm HI component (only ~ 4.3% of the HI mass is WNM or WIM).
  - 21 cm observations indicate that more the 60% of the HI within 500 pc of the Sun is actually in the warm phase.

A SMALL CLOUD

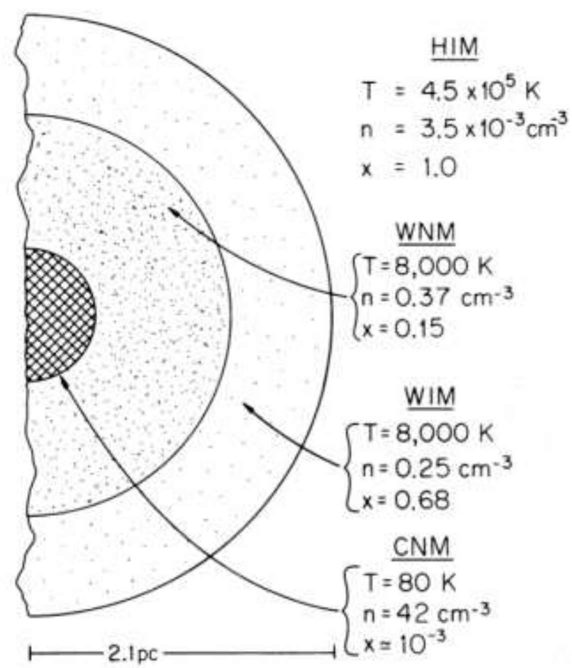


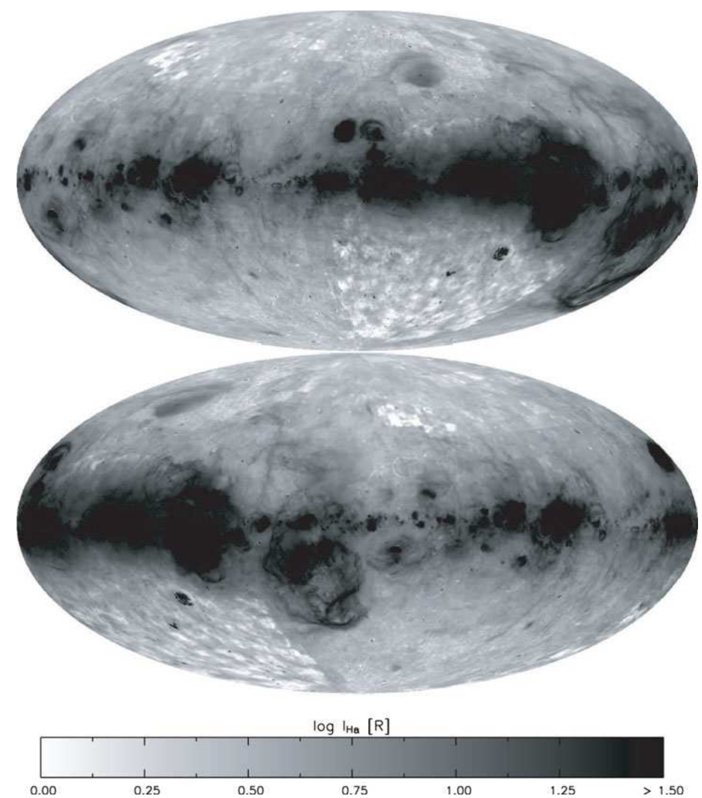
FIG. 1

Feedback from Massive Stars

- The momentum flux left over at the end of a SNe's radiative expansion phase creates a turbulent pressure. [BB]
- This turbulent pressure grows relative to the thermal pressure as $Q^{3/4}$.
- It follows that when SNe stir up the ISM, and Q becomes large, then the turbulent pressure will puff up the disk.
- A disk with a larger scale height has lower density. And the lower density suppresses star formation.

Warm Ionized Medium

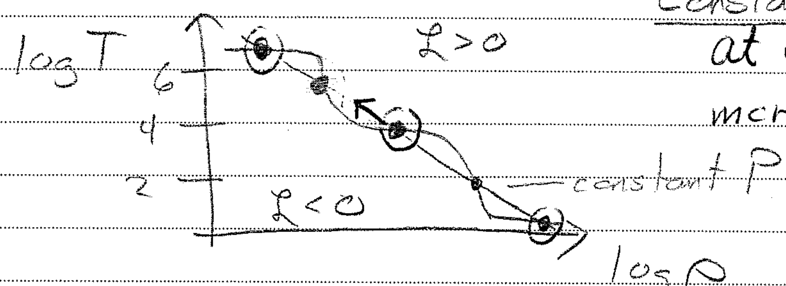
- A.ka. Reynolds layer
- Total energy requirement exceeds the KE from supernova, so OB stars seem like the only viable energy source
- Requires the equivalent of 1 O4 star (or 15 B0 stars) per kpc^2
- Low ionization parameter consistent with being ~500 pc from the nearest O7 star.
- About 15% of all ionizing photons leak out of HII regions through holes in the HI distribution



A multiphase is likely to develop in a cooling medium.

Isobaric Medium $\left(\frac{\partial \mathcal{L}}{\partial T}\right)_\rho < 0 \Rightarrow$ Thermal Instability

Note: $\mathcal{L} = \frac{(C - \mathcal{H})}{\rho}$ is the net cooling-heating rate per unit mass.



Consider isobaric perturbations
at ⊙, increase T and gas cools more efficiently ⇒ stable.

at •, increase T and gas cools less efficiently, so it is unstable.

CIE Cooling Function → 3 thermally stable phases

$\sim 10^6$ K
$\sim 10^4$ K
~ 10-100 K

Have a homogeneous gas parcel in thermal equilibrium. Perturb a blob of gas away from TE in a manner such that its pressure is kept equal to that of the surrounding medium.

Pressure equilibrium assumption is good provided the sound crossing time is short compared to the cooling timescale.

Field + 1969
Mckee & Ostriker 1977

Two-phase model

Net cooling $\mathcal{L} \equiv n^2\Lambda - n\Gamma = \mathcal{C} - \mathcal{H}$
= cooling rate − heating rate

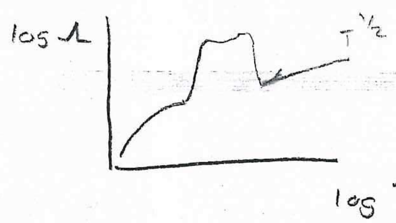
Thermal Eq. Curve defined by $\mathcal{L} = 0$.

$$n\Gamma = n^2 \Lambda$$

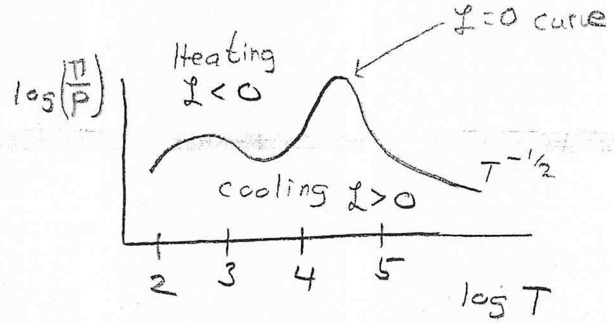
$$\Gamma = n\Lambda$$

$$\frac{\Gamma}{n k T} = \frac{\Lambda(n,T)}{kT}$$

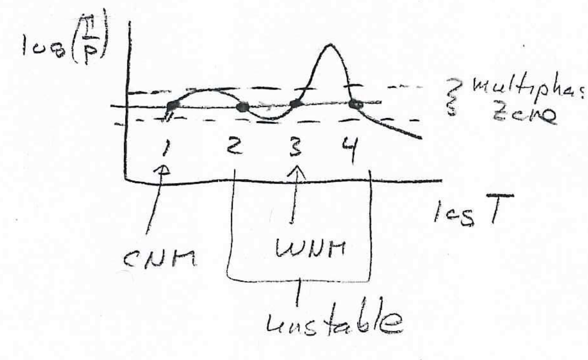
In LDL, $\Lambda(n,T) \approx \Lambda(T)$ is independent of density.



⟹



Follow example of Field, Goldsmith, & Habing ∃ ?
all heating due to CRs.

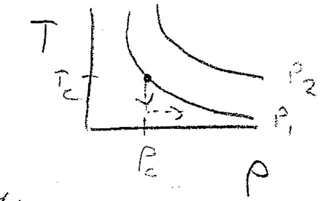


The Γ_{CR} rate is independent on n and T.
And the heating rate is a horizontal line.

For a range of pressures, there are 4 equilibrium points.

Instability criterion at constant pressure $\left(\frac{\partial \mathcal{L}}{\partial T}\right)_P < 0$

$$\left.\frac{\partial \mathcal{L}(\rho, T)}{\partial T}\right|_{P_0} = \left.\frac{\partial \mathcal{L}}{\partial T}\right|_{\rho_0} + \left.\frac{\partial \mathcal{L}}{\partial T}\right|_{T_0}$$



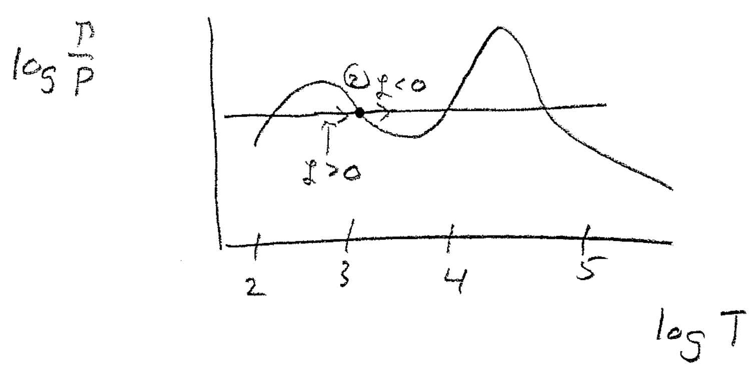
need to write this in terms of ρ since T is held at T_0.

$$T = \frac{P\bar{m}}{k\rho}$$

$$\partial T = -\frac{P\bar{m}}{k}\rho^{-2}\,\partial\rho$$

$$\partial T = -\frac{T_0}{\rho_0}\,\partial\rho$$

$$\left.\frac{\partial \mathcal{L}(\rho, T)}{\partial T}\right|_{P_0} = \left.\frac{\partial L}{\partial T}\right|_{\rho_0} - \frac{\rho_0}{T_0}\left.\frac{\partial \mathcal{L}}{\partial \rho}\right|_{T_0} < 0$$



So $\frac{\partial \mathcal{L}}{\partial T}$ decreases across point ②. The gas cools less efficiently as it heats up. So it heats up more – until it reaches a stable phase due to the increased cooling efficiency of Lyα.

Hot Intercloud Medium

Tielens p. 286
Cox & Smith 1974

Porosity Parameter

$$Q = \xi \, V_{SNR} \, \tau$$

- ξ — supernova rate per unit volume
- V_{SNR} — Volume of a SNR $= \frac{4}{3}\pi [R(t)]^3$
- τ — SNR lifetime

For low ξ, Q is the fraction of the total ISM filled by hot SNRs.

Example: Use $R(t)$ in Radiative Expansion phase
Find τ_{SN} when v drops to random speed in ISM and SNR merges with ISM.

$$Q \simeq 0.12 \, N_{SN} \left(\frac{E_{SN}}{10^{51} erg} \right)^{44/45} n_0^{-44/45}$$

N_{SN} ← # of SNe per 100 years in 150 Kpc^3

So for $n_0 = 0.1 \, cm^{-3}$, we have $Q = 1.8$

For a uniform medium with constant Q, the time averaged fraction of the medium filled with hot gas is

$$f_{HIM} = \frac{Q}{1+Q}$$

$$= \frac{1.8}{1+1.8} \simeq 0.6$$

The turbulent pressure due to SN KE follows from the momentum left over at the end of the radiative expansion phase

This momentum flux density defines a turbulent pressure.

$$\underbrace{\rho v^2}_{\text{pressure}} = \underbrace{\rho_0 U_{SNR} \frac{c_s}{4\pi R^2}}_{\text{momentum flux}}$$

In terms of the thermal pressure

$$\frac{\langle \rho v^2 \rangle}{P_0} \simeq 0.9\, Q^{3/4}$$

when SN stir up the ISM, Q becomes large and the high turbulent pressure puffs up the disk.