ISM 101
or
The 101 Faces of the ISM

Reading material:
Draine – Physics of the interstellar and intergalactic medium (2011 book)
Cox – The Diffuse interstellar medium (2005 review)
Pogge - Introduction to the Interstellar Medium (2008 lecture notes)
…

Composition of the ISM

ISM: all the matter in galaxies except stars (including various energy fields).

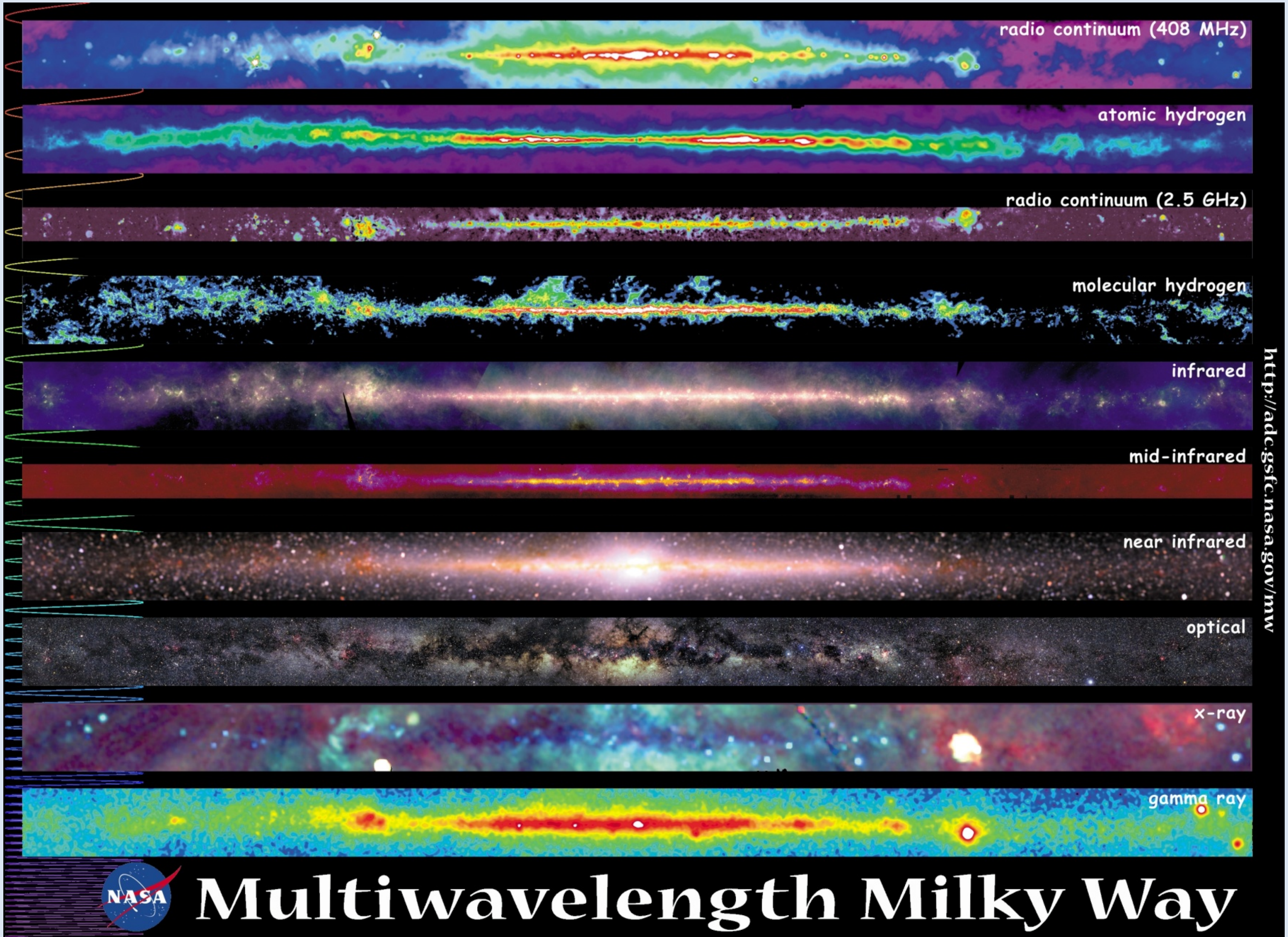
Multiwavelength Milky Way

Composition

Equilibrium

Heating & Cooling

Structure



ISM INTRO

Discrete objects in the ISM

HII regions ("bright nebulae")

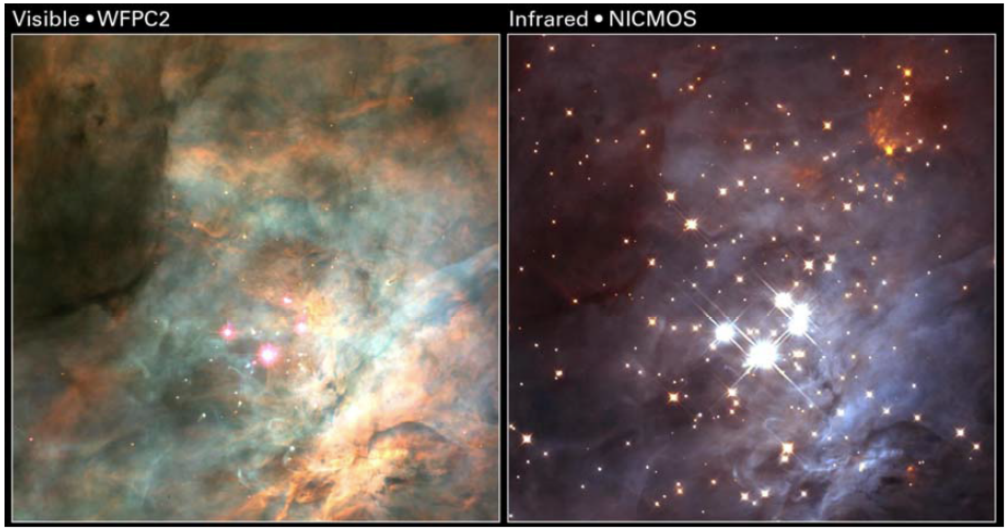


Figure I-2: HST Visible light (left) and Near-IR 1–2μm (right) images of the core of the Orion Nebula, a classical bright HII region [Credit: NASA and K. Luhman – STScI-PRC00-19]

Strong emission lines + weak continuum
Powered by O&B stars (birth of stars)

Discrete objects in the ISM

Obscure regions("dark nebulae")

Figure I-1: Dark clouds towards the Milky Way in Sagittarius. [Credit: John P. Gleason, Celestial Images]

Horsehead nebula

Opaque parts of HII regions

Discrete objects in the ISM

Composition

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Planetary nebulae

Figure I-3: Planetary Nebulae [Credit: Hubble Heritage Project, NASA/AURA/STScI, and NOAO (center)].

UV photoionized ejecta from old stars

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Discrete objects in the ISM

Young Supernova remnants

Figure I-4: Crab Nebula, young SNR (AD1054). [Credit: VLT Kueyen+FORS2]

Photoionized by UV synchrotron radiation from relativistic electrons of SN

Discrete objects in the ISM

Composition
Equilibrium
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Structure

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Young Supernova remnants

Figure I-5: The Cygnus Loop, an old SNR. This image shows emission from the shockwaves impinging on the ambient ISM (sharp filaments). [Credit/Copyright: Jerry Lodriguss, www.astropix.com]

Photoionized by X-rays from SN
mechanically heated cooling regions

Diffuse gas in the ISM

γ-rays

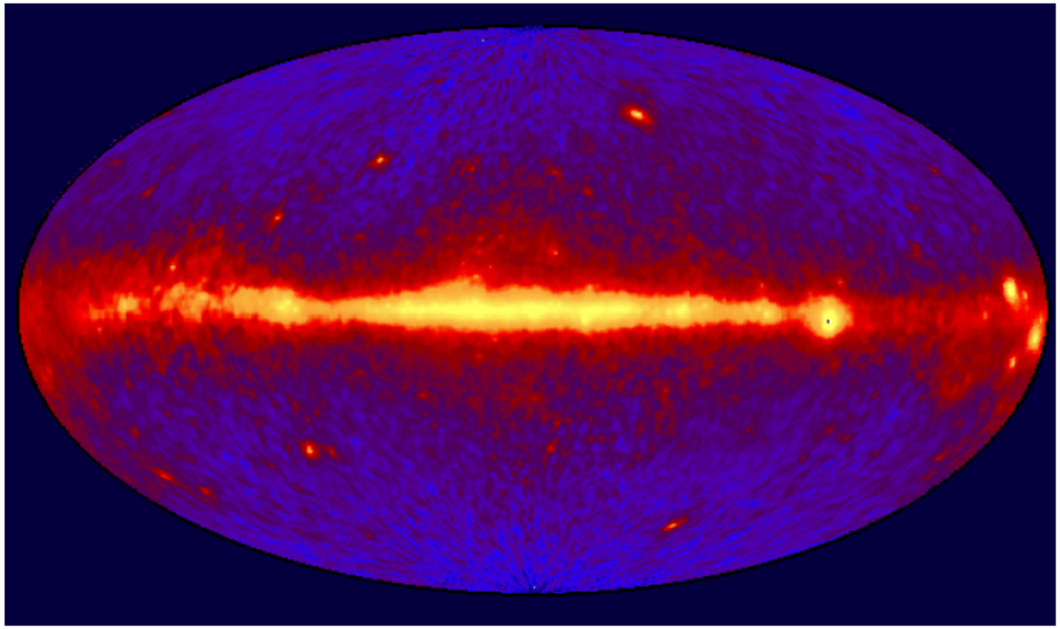

Figure I-12: CGRO EGRET γ-ray (>100MeV) map of the Galaxy [Credit: NASA/GSFC]

MeV particles from shock acceleration/relativistic flows …

Diffuse gas in the ISM

Composition

Equilibrium

Heating & Cooling

Structure

X-rays (HII) "coronal gas"

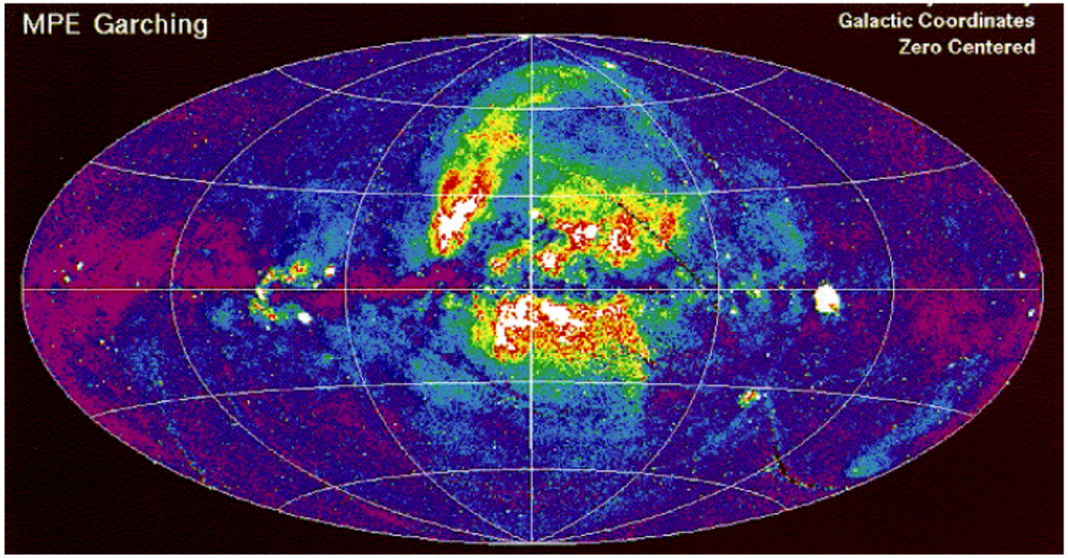

Figure I-11: ROSAT Soft X-ray (0.5-0.9keV) map of the Galaxy [Credit: RASS, MPE Garching]

Starlight and hot (> 10^5 K) gas
n~$0.003 cm^{-3}$
Line emission from ionized metals.
High altitude (3kpc)

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Diffuse gas in the ISM

Composition

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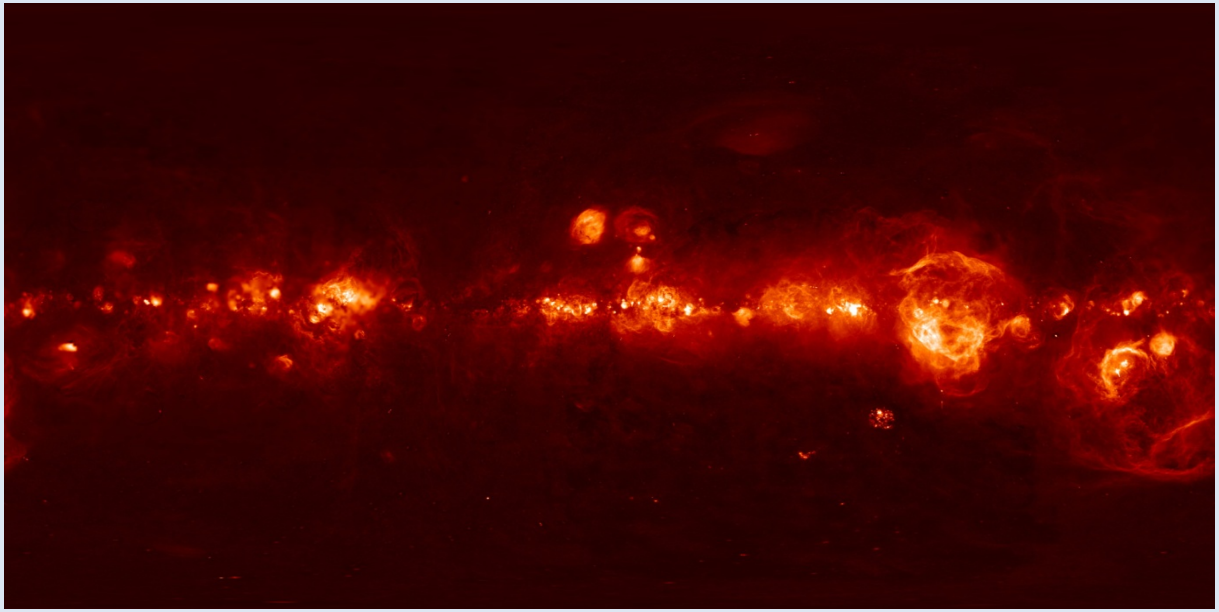
UV absorption (HI and H_2)

No pretty pictures – only spectral lines

Diffuse H_2 and HI (electronic transition)

Diffuse gas in the ISM

H-α maps (HII diffuse gas)



Composite (WHAM+ VTSS + SHASSA)-- Finkbeiner (2003)

$\nu_{3\to2}$ (Hydrogen) – red visible light
n~0.1 cm^{-3}, T~8000K

Diffuse gas in the ISM

Molecular lines (H_2)

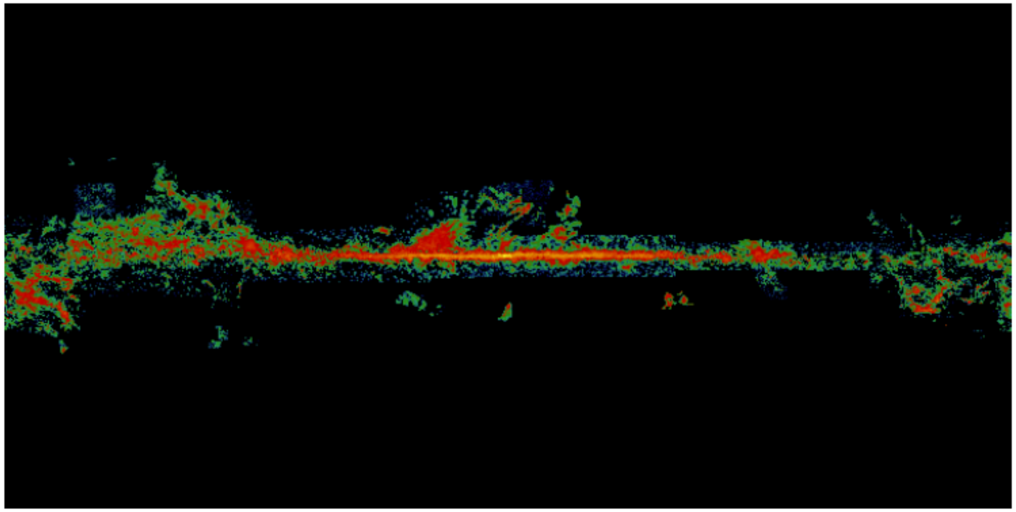


Figure I-8: CO J=1–0 (λ=1.6mm) emission-line map of the Galaxy [Dame, Hartmann, & Thaddeus, 2001, ApJ]

Micro-mm wavelength. Concentrated in GMCs. n~200cm^{-3} , T~10K, Line ratios can fix density and temperature.

Diffuse gas in the ISM

Composition
Equilibrium
Heating & Cooling
Structure

Infrared emission (HI, H_2)

IR from thermal emission of dust grains

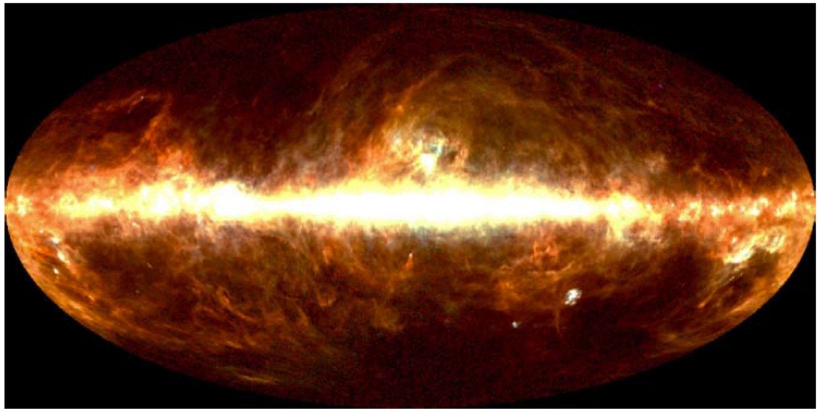


Figure I-9: COBE Far-Infrared (60-240μm) map of the Galaxy [Credit: NASA/GSFC]

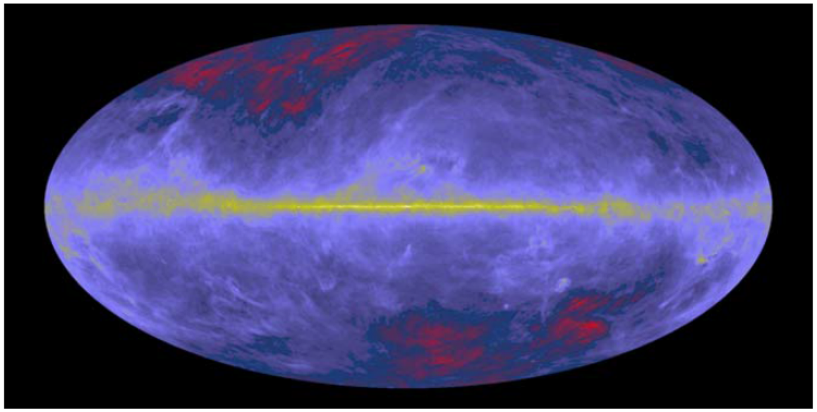
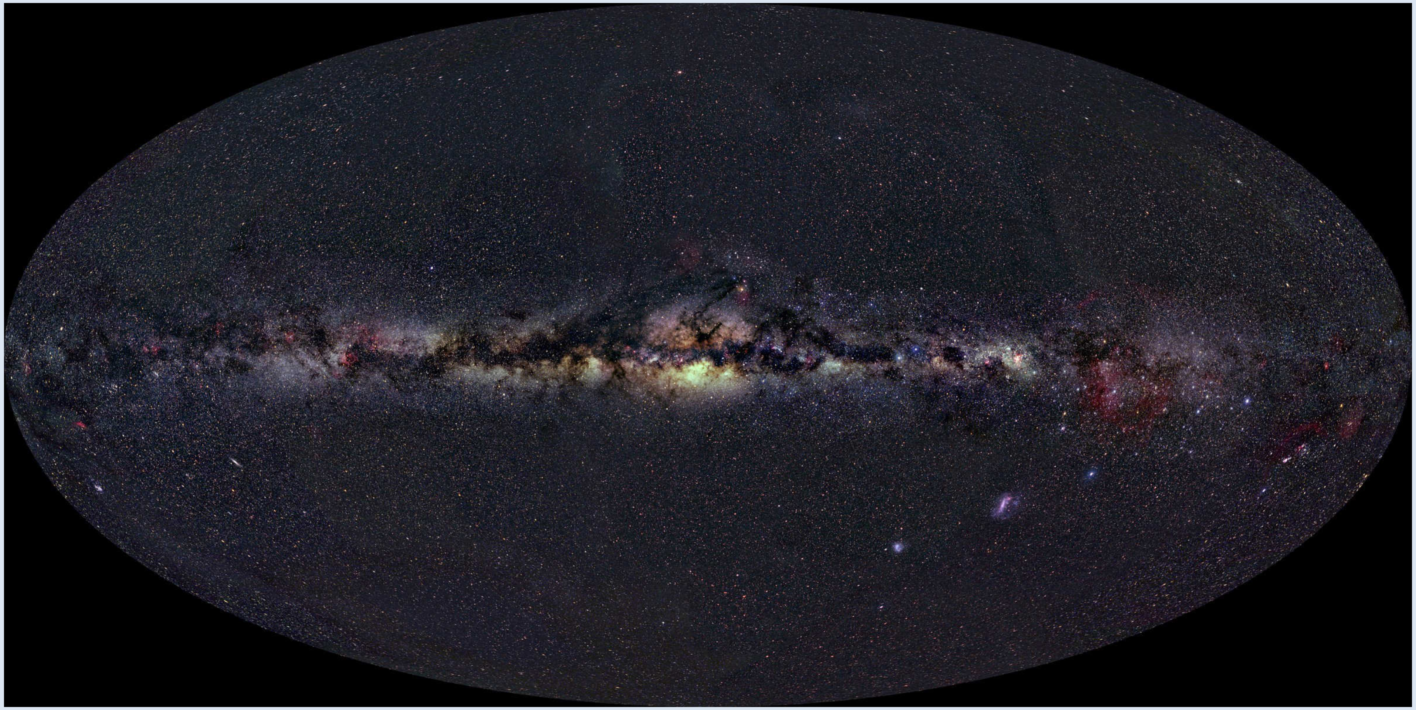


Figure I-10: Dust column density map of the Galaxy from IRAS & COBE data [Schlegel, Finkbeiner & Davis 1998]

Diffuse gas in the ISM

Dust and molecules



Grain size: 5-3000A°. Mass~1%.
Absorption, reddening,extinction, polarization, IR emission

Diffuse gas in the ISM

Composition
Equilibrium
Heating & Cooling
Structure

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21 cm (cold HI)

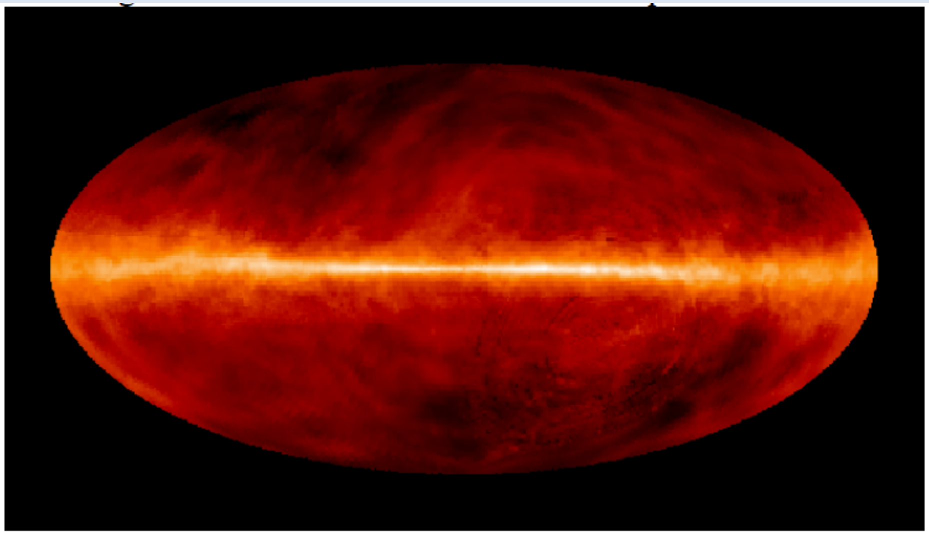

Figure I-7: HI 21cm emission-line map of the Galaxy. [Dickey & Lockman 1990]

Composite (WHAM+ VTSS + SHASSA)-- Finkbeiner (2003)

Hyperfine transition of s1 level spin –
1.4Ghz radio
100K<T<8000K

Typical ISM parameters:

Composition

Equilibrium

Heating & Cooling

Structure

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Density: $10^{-3} - 10^{2}$ particles/cm^3

Temperature: $10 - 10^{7}$ K

Pressure (@midplane): $3X10^{-12}$ dyn/cm^2 or p/k_B=22000 K/cm^3

Magnetic field: B~3μG

Element	Abundance	Element	Abundance
H	1.00	Mg	4.2×10^{-5}
He	0.075	Al	3.1×10^{-6}
C	2.5×10^{-4}	Si	4.3×10^{-5}
N	6.3×10^{-5}	S	1.7×10^{-5}
O	4.5×10^{-4}	Ca	2.2×10^{-6}
Na	2.1×10^{-6}	Fe	4.3×10^{-5}

Galactic distribution

MW = Sb/Sc ordinary spiral galaxy

Atomic gas radial dist. – 18kpc

Molecular gas radial dist. 3kpc

Thin! 75pc for H_2. 100-300pc for HI

HII and dust mostly within spiral arms

Kinetic equilibrium

Maxwellian Distribution of particle velocities

$$f(\mathbf{v})d^3v = \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right) dv_x dv_y dv_z$$

$$v^2 = (v_x^2 + v_y^2 + v_z^2)$$

$$\mu \equiv \text{reduced mass of the particles}$$

$$t_{ee} \approx 10^4 \left(\frac{E_e}{1\text{ eV}}\right)^{3/2} n_e^{-1} \text{ sec}$$

$$t_{eH} \approx 2\times10^7 \left(\frac{E_e}{1\text{ eV}}\right) n_e^{-1} \text{ sec}$$

T – kinetic temperature

Excitation equilibrium

Bolzmann equation (for LTE)

$$\frac{n_u^*}{n_l^*} = \frac{g_u}{g_l} e^{-\Delta E_{ul}/kT}$$

T – kinetic temperature, $g_i=(2J_i+1)$, ΔE – energy gap

Since LTE is almost never gained, we define excitation temperature, T_{exc}

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\Delta E_{ul}/kT_{exc}}$$

Ionization equilibrium

Composition

Equilibrium

Heating & Cooling

Structure

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The main ionizing agent is radiation

$$X^r + h\nu \leftrightarrow X^{(r+1)} + e^-$$

$$N(X^r)N(photons)\sigma_{ionize}c = N(X^{(r+1)})N_e\sigma_{recomb}\left\|\mathbf{v}_X - \mathbf{v}_e\right\|$$

$$\frac{n(X^{(r+1)})n_e}{n(X^r)} = \frac{n_{photons}\langle\sigma_{ionize}\rangle c}{\langle\sigma_{recomb}v\rangle}$$

$$\frac{n(X^{(r+1)})}{n(X^r)} = \frac{1}{n_e}\left(\frac{\Gamma}{\alpha(T)}\right)$$

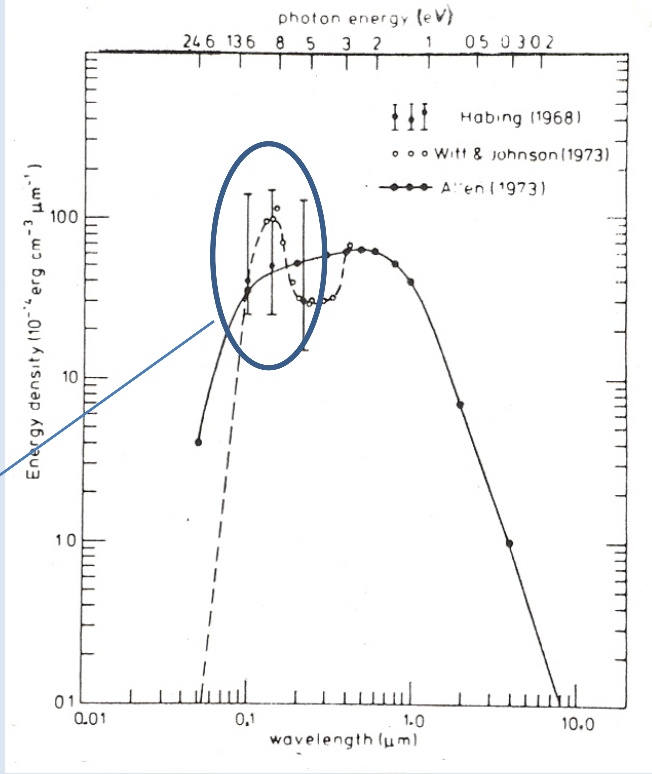
Γ – radiation field term

α(T) – Recombination rate

Radiation equilibrium

Planck Formula

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_\mathrm{B}T}} - 1}$$



Peak at 2000A° (UV) – 10^4K
But energy density is 2.7K!!!

Pressure equilibrium

$$c_s \cong 10\sqrt{T_4}\,km/\sec \cong 10\sqrt{T_4}\,pc/Myr$$

Pressure equilibrium is achieved.
However, what contributes to the pressure ???

State of equilibrium

✔	Kinetic equilibrium	Short timescales
✘	Excitation equilibrium	Radiation
✘	Ionization equilibrium	Long recombination times, photoelectric effect
✘	Radiation equilibrium	
✔	Pressure equilibrium	

Thermal (excitation, ionization, radiation) equilibrium requires detailed balance.
This is almost never the case in ISM.

Energetics

Composition

Equilibrium

Heating & Cooling

Structure

Thermal Energy, u_{th}

$$u_{th} = \frac{3}{2}P = 0.39\frac{P/k}{3000\ \mathrm{cm}^{-3}\ \mathrm{K}}\ \mathrm{eV\ cm}^{-3}$$

Hydrodynamic Energy, u_{hydro}

$$u_{hydro} = \frac{1}{2}\rho\left\langle v^2\right\rangle = 0.13\left(\frac{n_H}{cm^{-3}}\right)\left(\frac{\sigma_{1\mathrm{D}}}{5\ \mathrm{km\ s}^{-1}}\right)^2\ \mathrm{eV\ cm}^{-3}$$

Magnetic Energy, u_{mag}

$$u_{mag} = \frac{B^2}{8\pi} = 0.22\left(\frac{B}{3\ \mu\mathrm{G}}\right)^2\ \mathrm{eV\ cm}^{-3}$$

Cosmic Rays, u_{CR}

$$u_{CR} = 0.8\ \mathrm{eV\ cm}^{-3}$$

Starlight, u_{stars}

$$u_{stars} = 0.5\ \mathrm{eV\ cm}^{-3}$$

Cosmic Background Radiation, u_{CBR}

$$u_{CBR} = 0.26\ \mathrm{eV\ cm}^{-3}\ \text{for T=2.725K}$$

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Hydrostatic equilibrium

Composition

Equilibrium

Heating & Cooling

Structure

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Vertical distribution of mass

molecular: $0.58\ \exp[-(z/81\,\mathrm{pc})^2]$ CO emission

cold HI: $0.57 * 0.7\ \exp[-(z/127\,\mathrm{pc})^2]$

warm HIa: $0.57 * 0.18\ \exp[-(z/318\,\mathrm{pc})^2]$

warm HIb: $0.57 * 0.11\ \exp(-|z|/403\,\mathrm{pc})$

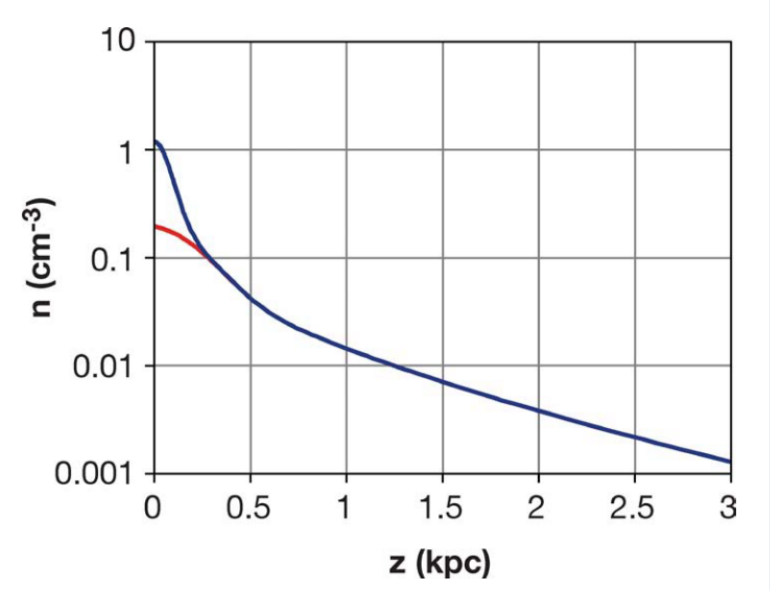
, 21 cm Lα

HII Regions: $0.015\ \exp(-|z|/70\,\mathrm{pc})$ Hα, Pulsars

diffuse HII: $0.025\ \exp(-|z|/1000\,\mathrm{pc})$. Hα, UV absorption, Soft X

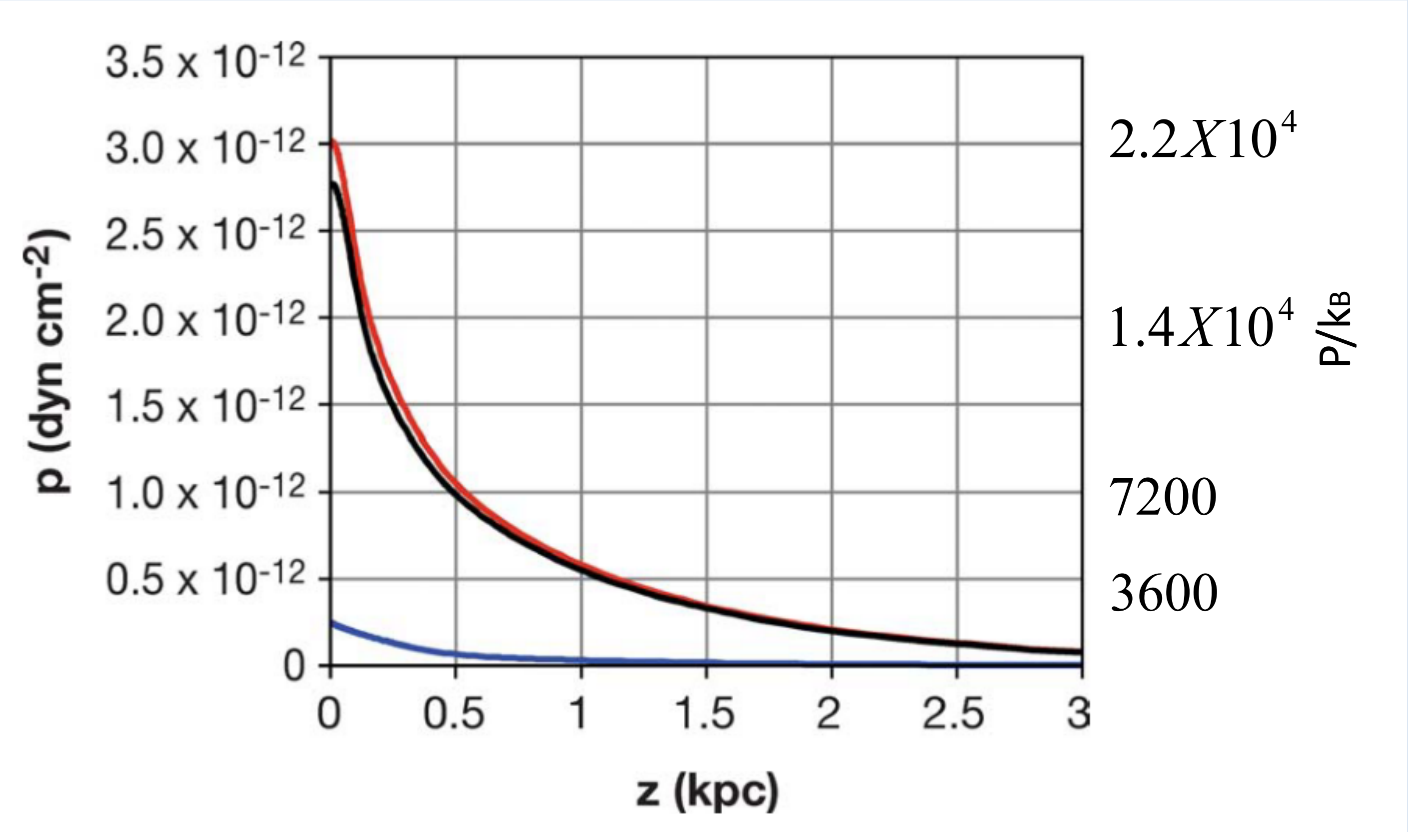
Ferriere 2001

Extremely Hard to combine into a comprehensive picture



Vertical hydrostatic equilibrium

- Most of the pressure (9/10) comes from non-thermal components



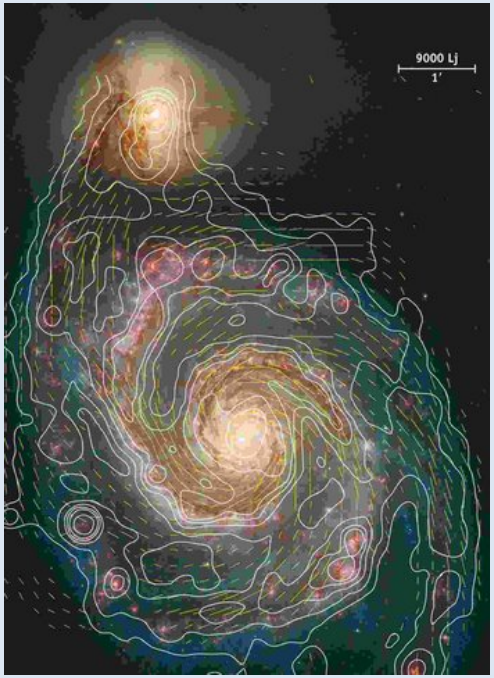
Magnetic fields

- Stellar polarimetry
- Zeeman splitting of 21 cm
- Faraday rotation of linearly polarized radio
- Synchrotron emission

B

$$B \sim 1.5 + O(5)\mu G$$

$$l_{corr} \sim 1pc$$



M51, HST,
MPIfR Bonn

Magnetic fields

- Stellar polarimetry
- Zeeman splitting of 21 cm
- Faraday rotation of linearly polarized radio
- Synchrotron emission

B

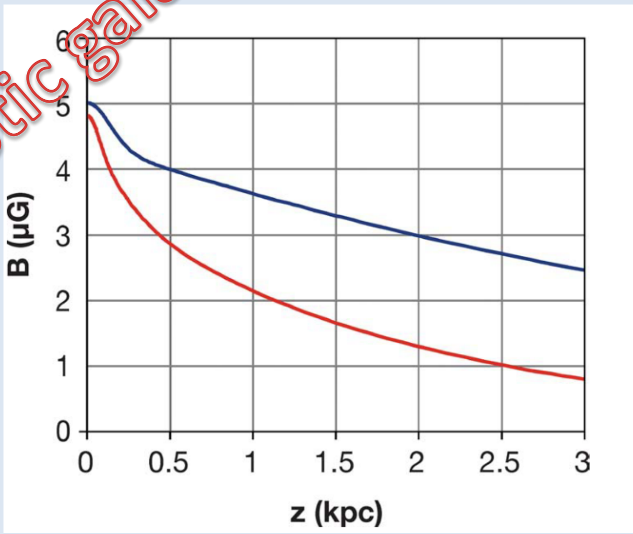
The elastic galaxy

$$B \sim 1.5 + O(5)\mu G$$

$$l_{corr} \sim 1pc$$

$$P = \frac{(5\cdot 10^{-6})^2}{8\pi} \sim 10^{-12} erg\ cm^{-3}$$

$$\sim 7200K\ cm^{-3} \sim 0.6eV\ cm^{-3}$$



Cosmic rays

- Π0 meson production
- Bremsstrahlung emission
- Inverse Compton emission
- Cosmic ray chemistry
- Synchrotron emission

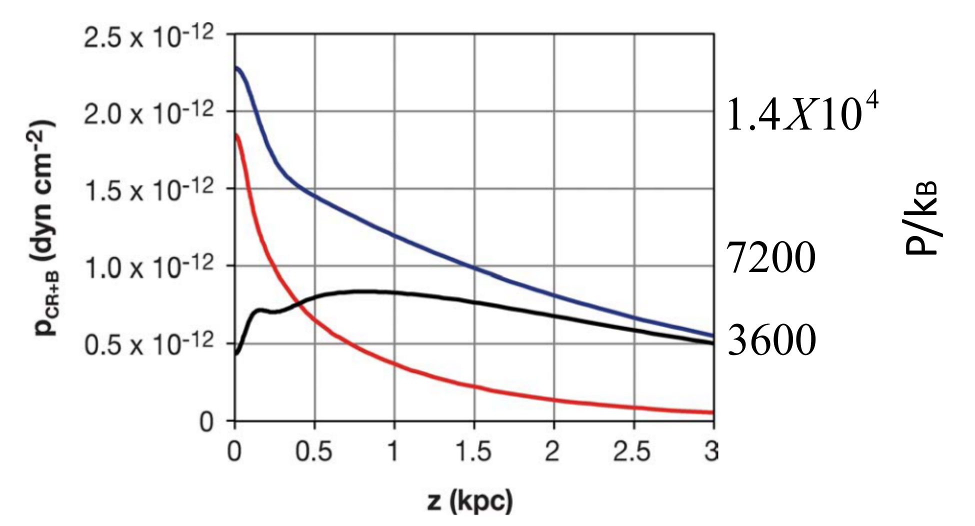
Local ISM values (Extrapolated from solar winds):

$$P / k_B \sim 9500 K\ cm^{-3}$$

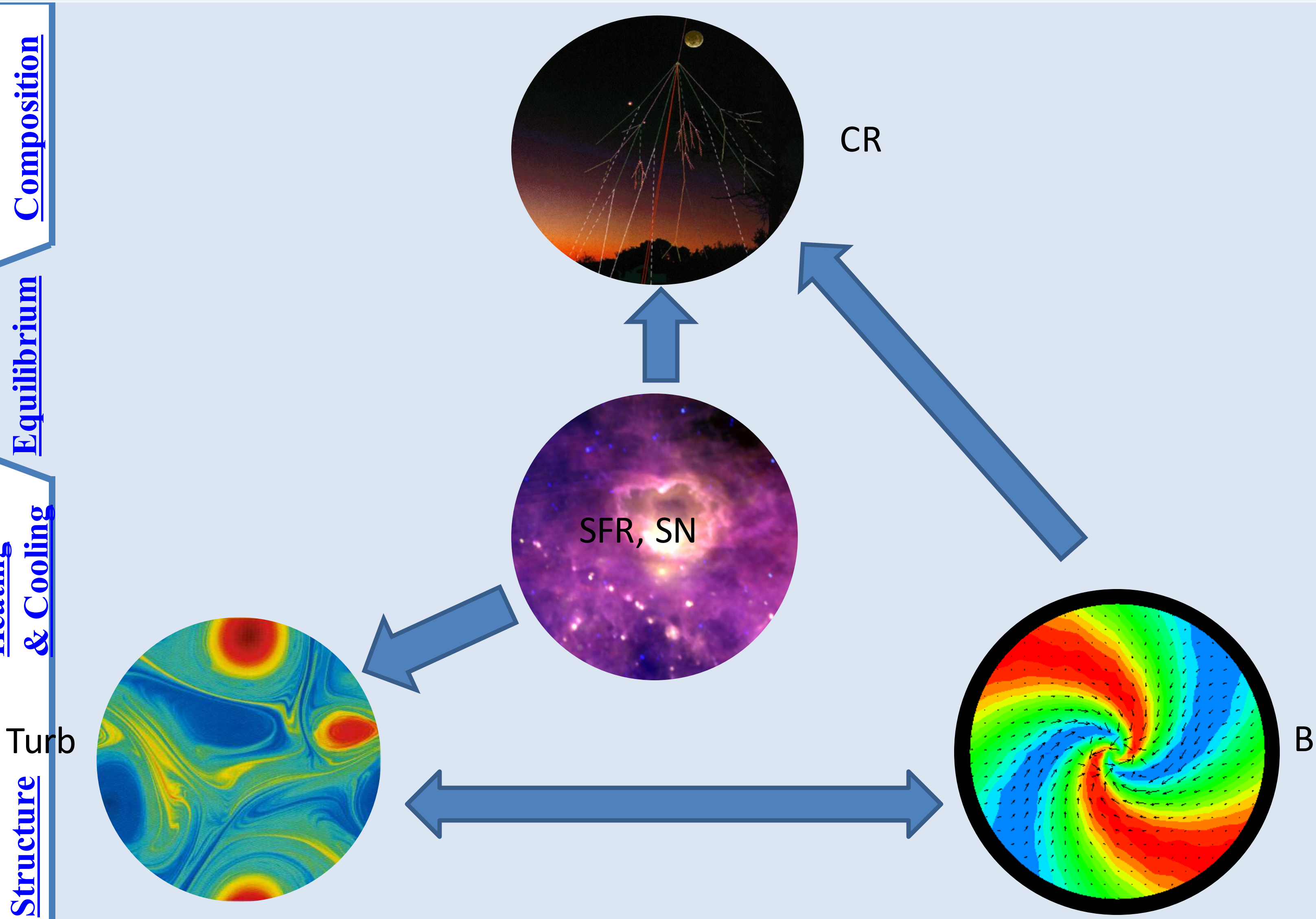
The leaky box model of CR

Synchrotron emission

- Depends on combination of B and CR
- Assuming:
  - CR electrons trace pressure
  - Equi-partition between B and CR
  - Normalization to local values



The equipartition hypothesis



Vertical model:

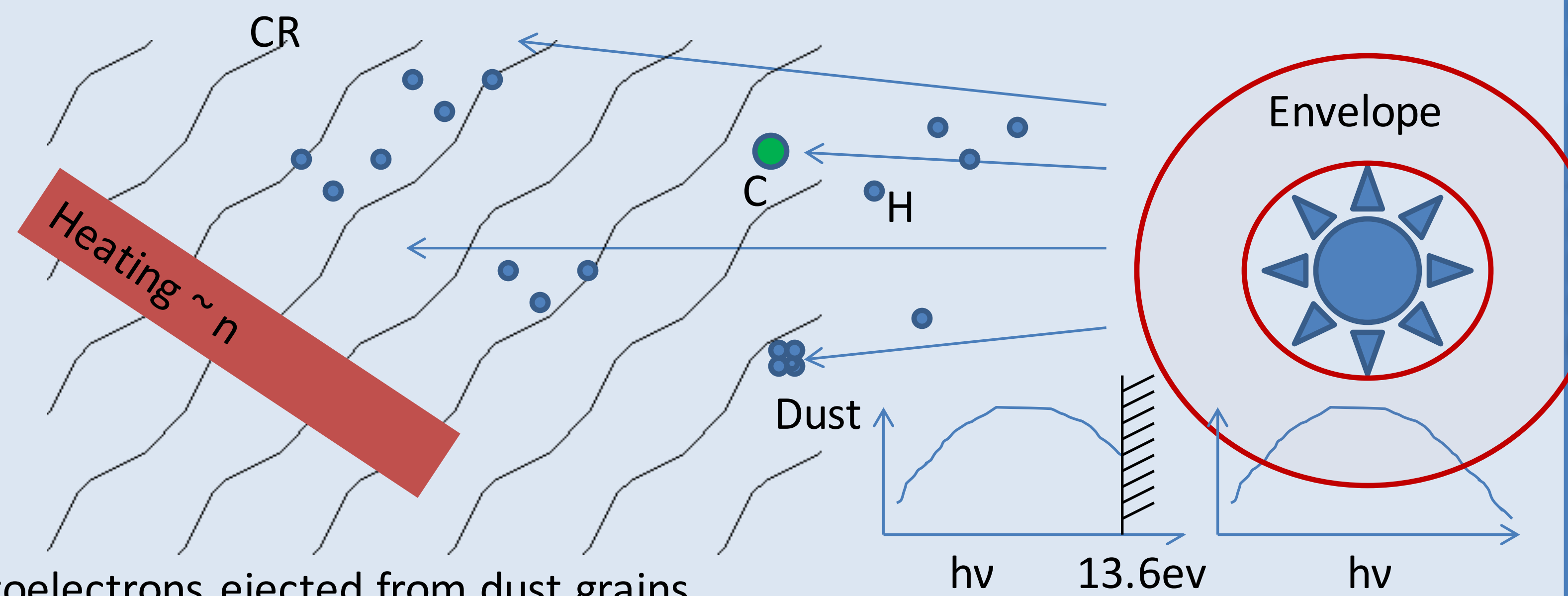
- The thermal pressure is about 1/10 of the total vertical pressure
- Equipartition conjecture between
  - Turbulence
  - Magnetic field
  - Cosmic rays
- It is plasma after all ;-)

Heating sources

Composition
Equilibrium
Heating & Cooling
Structure

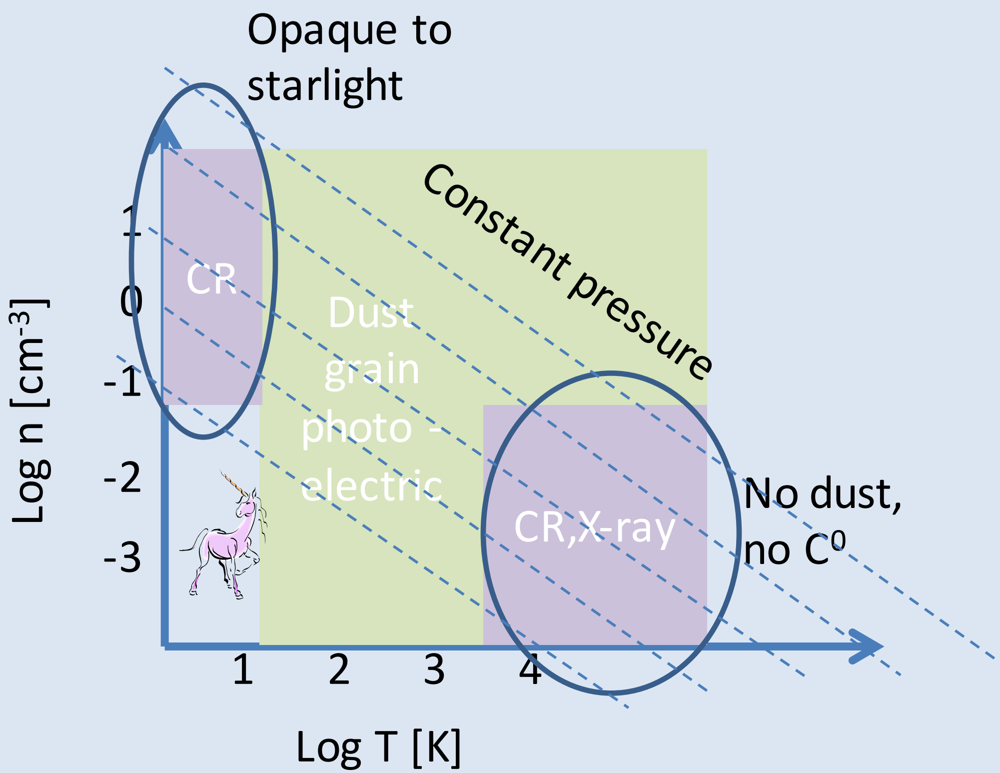
Ultimately, energy is gravitational + nuclear.

Specific mechanism depends on ISM conditions



Photoelectrons ejected from dust grains
Cosmic ray heating
Photoionization of metals
X-ray heating

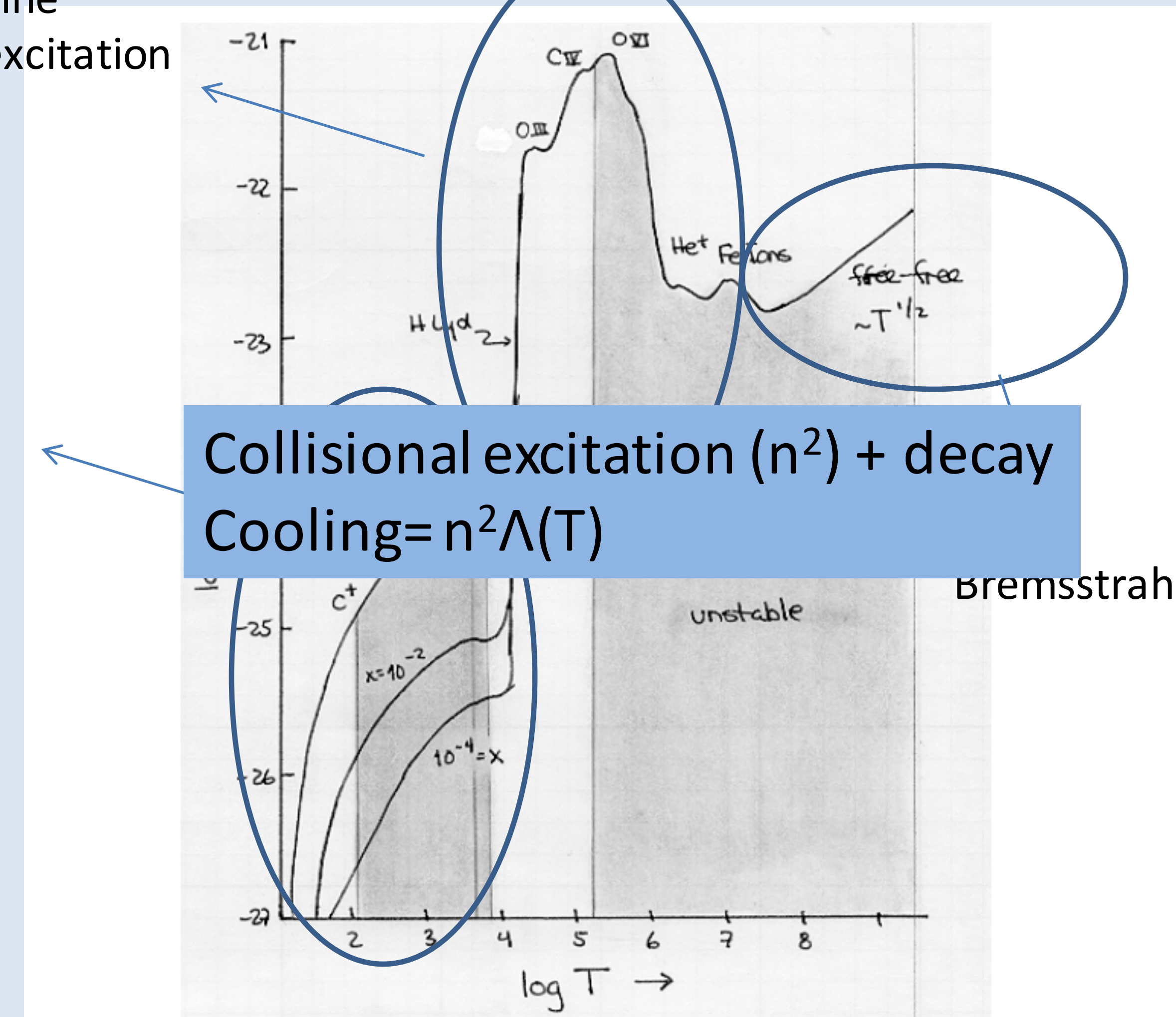
Heating


Opaque to
starlight
Constant pressure
CR
Dust
grain
photo -
electric
CR,X-ray
No dust,
no C^0
1
0
-1
-2
-3
Log n [cm^{-3}]
1
2
3
4
Log T [K]

Cooling.

Line excitation

Fine structure lines (metals only)



Collisional excitation (n^2) + decay

Cooling= $n^2\Lambda(T)$

Bremsstrahlung

Figure I-13: Interstellar Cooling curve adapted from Dalgarno & McCray (1972).

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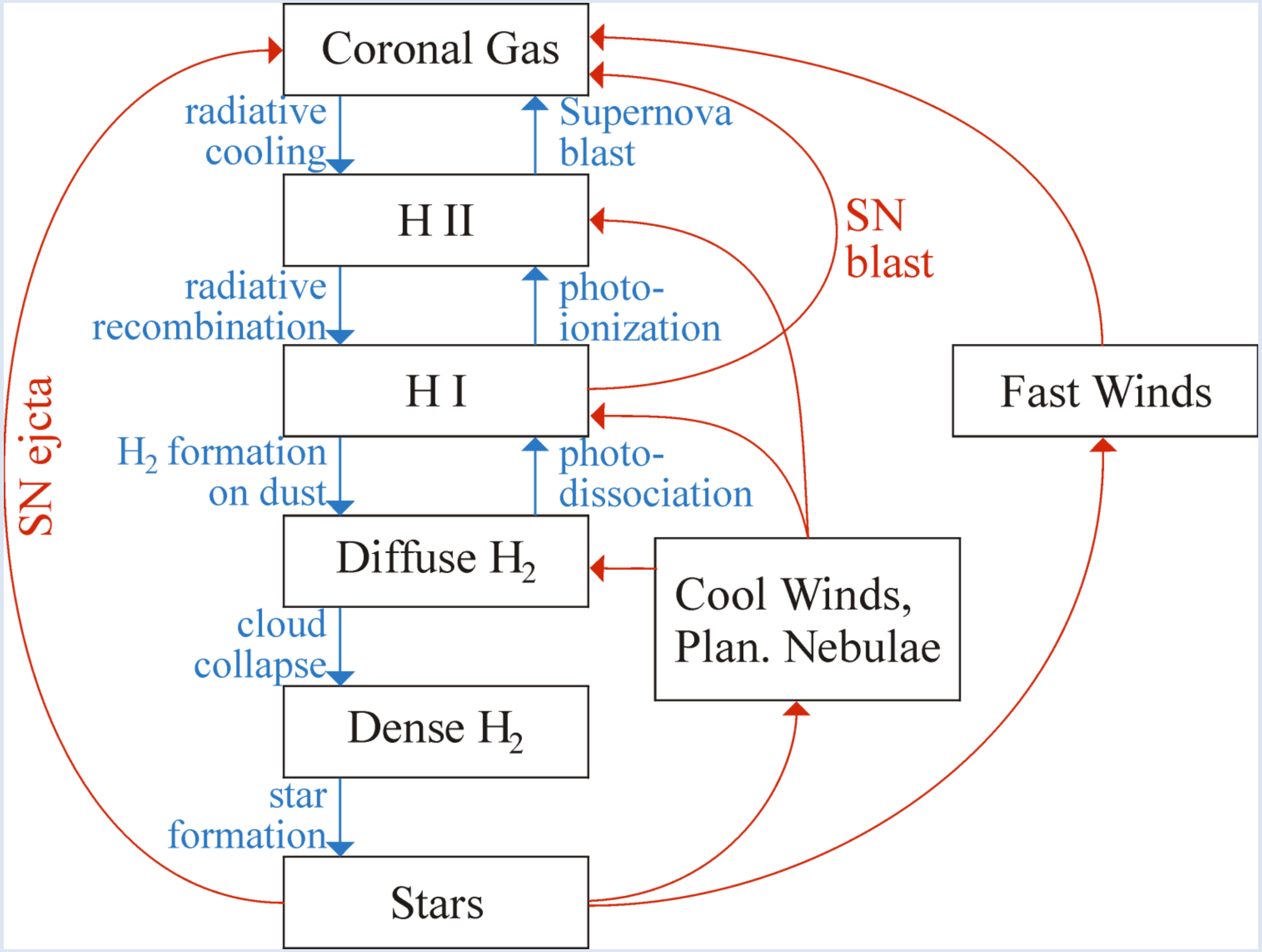
ISM life cycle



Hogerheijde 2010

Field (65) cooling instability

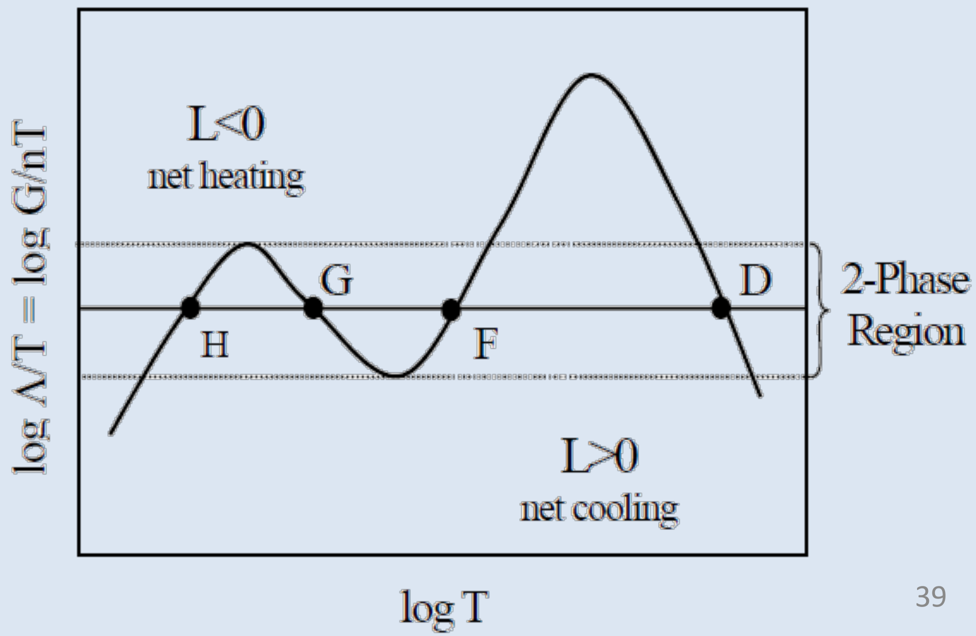
Requirements for stability

$$\left(\frac{d\Lambda_{tot}}{dS}\right)_{p,\rho} > 0$$

$$\Lambda_{tot} = n^2\lambda - n\Gamma = 0 \quad [{}^{erg}\!/\!_{cm^2\,\sec}]$$

$$\frac{\partial\lambda}{\partial T} > 0 \quad \text{isochoric}$$

$$\frac{\partial\lambda}{\partial T} > \frac{\lambda}{T} \quad \textit{isobaric}$$



Composition
Equilibrium
Heating & Cooling
Structure

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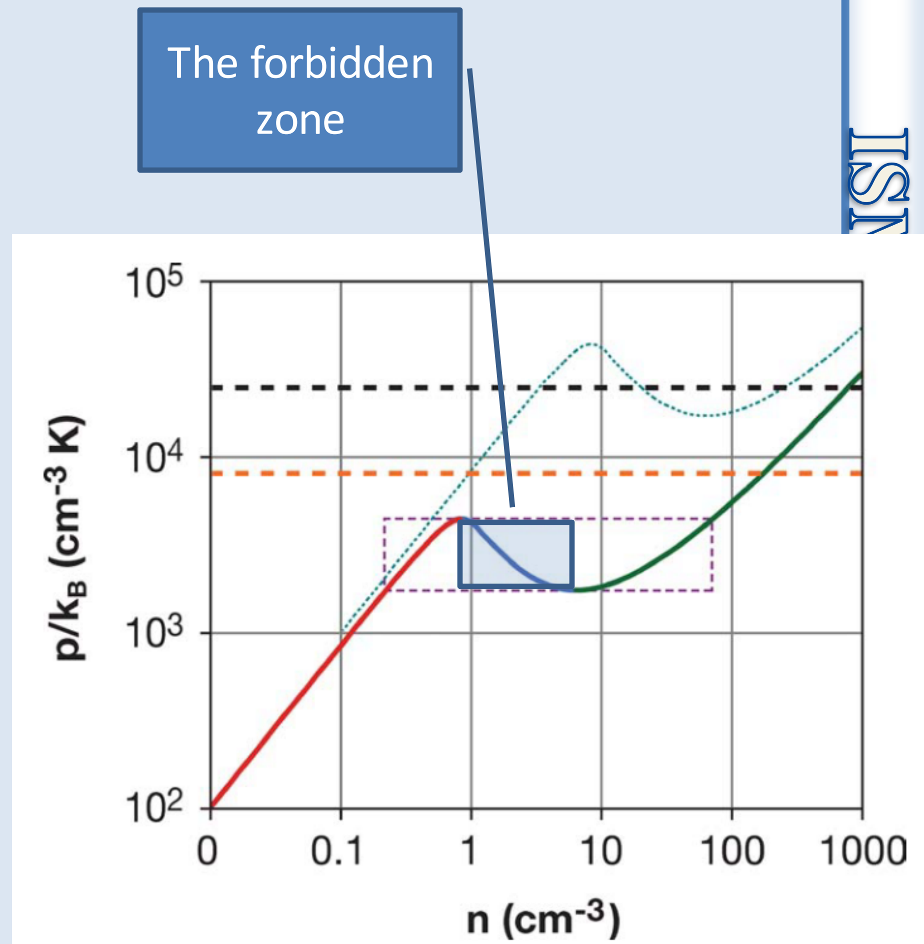
Thermal stability of the ISM

Two phase medium

(Field, Goldsmith & Habing, 1969)

- Assume density, Poly-aromatic hydrocarbon (PAHs) state, dust.
- Solve T(n) for balance between photoelectric + CR heating and radiative cooling + conduction
- Construct $P_{th}(n)$

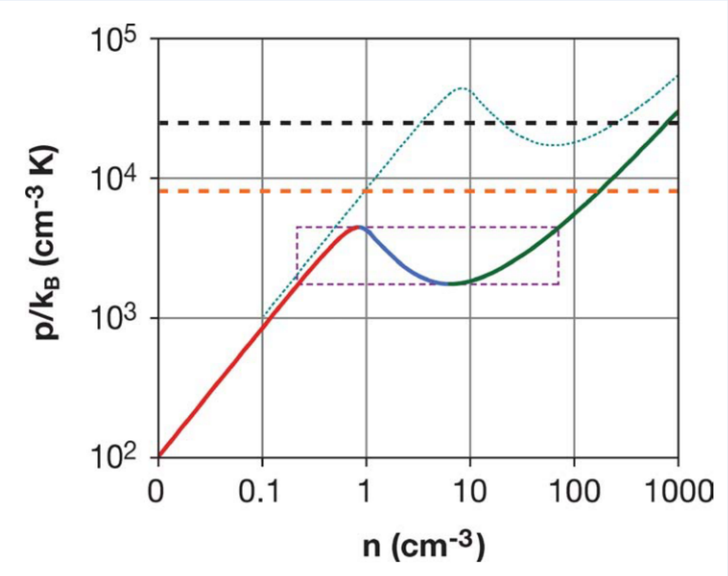
Building a cold clump from the hot phase takes too long



Wolfire et al. 2003

Surprises of two-phase models

1. Phase segregation not important
2. Thermal pressure might appear as pressure equilibrium
3. Voids (0 thermal pressure) allowed
4. Magnetic pressure does not correlate with density much
5. Forbidden n is actually common
6. On average, heating reduces cold cloud probability - feedback



Wolfire et al. 2003

Proposed subjects

1. Giant molecular clouds
2. Galactic magnetic fields
3. Nebulae physics
4. Phase models of the ISM
5. Cosmic radiation
6. Interstellar dust
7. Supernovae & winds
8. ISM shocks
9. Numerics of the ISM
10. Radiation transfer
11. Equation of state of the ISM

* Each talk must also cover relevant observational techniques