X. Two Phase ISM

A. Motivations

- ISM feeds star formation via molecular clouds
- ISM also feeds AGN activity
- Let us put some of the pieces together to better characterize the ISM

B. Heating of the ISM by Photoionization

- The dominant process is the photoionization of C

$$\gamma + \mathrm{C}^0 \to \mathrm{e}^- + \mathrm{C}^+ \tag{1}$$

  - ◇ O is more abundant but has IP = 13.6eV
  - ◇ C is the next most abundant and has IP = 11.3eV
- Process
  - ◇ Similar to heating in HII regions
  - ◇ Need to compare ionization energy against electron temperature

$$\Gamma_{\mathrm{C}^+} = n_e n_{\mathrm{C}^+} \alpha_{\mathrm{C}}(T) \left[\frac{1}{2} \left(h\nu_0 - h\nu_{\mathrm{C}} \right) - f \frac{3}{2} kT \right] \quad \mathrm{erg/s/cm^3} \tag{2}$$

$$\alpha_{\mathrm{C}}(T) = 1.4 \times 10^{-10}\, T^{-0.607} \mathrm{cm^3/s} \tag{3}$$

    - ▲ $h\nu_0 = 13.6$eV
    - ▲ $\frac{1}{2}$ is an approximation of the energy input
    - ▲ $f \sim 0.6$
    - ▲ $T \sim 100\mathrm{K} \Rightarrow \frac{3}{2} kT \sim 0.01$eV
- Consider n_{C^+}
  - ◇ Most of the Carbon in the ISM is C^+
    - ▲ HI regions absorb all photons with $h\nu > 1\,\mathrm{Ryd}$
    - ▲ But are filled with photons having $h\nu < 1\,\mathrm{Ryd}$
  - ◇ Ionization balance

$$n_{C^+} n_e \alpha_C = \zeta n_{C^0} \tag{4}$$

  - ◇ Ionization rate

$$\zeta = \int_{IP(C)/h}^{\nu_0} c n_\nu \sigma_C d\nu \tag{5}$$

$$\sigma_C = 1 \times 10^{-18}\,\mathrm{cm^2} \tag{6}$$

$$n_\nu \approx 1 \times 10^{-28}\,\mathrm{cm^{-3}} \quad \text{(UV starlight)} \tag{7}$$

$$\text{Therefore } \zeta = 2 \times 10^{-10}\,\mathrm{s^{-1}} \tag{8}$$

- ◇ Ion fractions

$$\frac{n_{\mathrm{C}^+}}{n_{\mathrm{C}^0}} = \frac{\zeta}{\alpha_C}\frac{1}{n_e} \sim \frac{23}{n_e} \gg 1 \;\text{ for }\; n_e \ll 1 \tag{9}$$

- ◇ Therefore

$$n_{\mathrm{C}^+} \approx d_{\mathrm{C}} n_H \frac{\mathrm{C}}{\mathrm{H}} \tag{10}$$

  - ▲ C/H = Abundance by number of C
  - ▲ d_{C} = Depletion of C onto dust grains
    - ○ C in dust grains do not participate
    - ○ $d_{\mathrm{C}} \approx 0.5$

- Estimate n_e
  - ◇ Assume all electrons come from Carbon
  - ◇ Decent but wrong assumption

$$n_e = d_{\mathrm{C}} \frac{\mathrm{C}}{\mathrm{H}} n_H \tag{11}$$

- Altogether, the heating rate is

$$\frac{\Gamma_{\mathrm{C}^+}}{n_H^2} = (1.2\mathrm{eV}) \left(\frac{\mathrm{C}}{\mathrm{H}} d_C \right)^2 \alpha_C \tag{12}$$

C. Cooling in HI Regions: 158μ

- The low electron density implies the excitation of forbidden states is minimal
- Excitation of fine-structure states and Lyα dominates
- Consider the cooling from a 2-level system via collisions with electrons and HI atoms

$$\Lambda = n_e n_j \gamma^e_{jk} E_{jk} + n_{\mathrm{HI}} n_j \gamma^{\mathrm{HI}}_{jk} E_{jk} \quad (\mathrm{erg/s/cm^3}) \tag{13}$$

  - ◇ Assume the ground state is heavily populated

$$j = 1, \;\; n_j(X^+) = n(X^+) \tag{14}$$

  - ◇ Cooling rate is then

$$\frac{\Lambda}{n_H^2} = \frac{n_e}{n_H}\frac{n(X^+)}{n_H}\gamma^e_{jk} E_{jk} + \frac{n(X^+)}{n_H}\gamma^{\mathrm{HI}}_{jk} E_{jk} \tag{15}$$

$$= \frac{n(X^+)}{n_H} E_{jk} \left[x\gamma^e_{jk} + (1-x)\gamma^{\mathrm{HI}}_{jk} \right] \tag{16}$$

  - ◇ When do electron collisions dominate?

$$x\gamma^e_{jk} > \gamma^{\mathrm{HI}}_{jk} \tag{17}$$

$$x > \frac{\gamma^{\mathrm{HI}}_{jk}}{\gamma^e_{jk}} \approx \frac{v_H \sigma_H}{v_e \sigma_e} \approx 2.5 \times 10^{-4} \tag{18}$$

  - ▲ This is roughly the electron fraction in HI regions
  - ▲ Therefore, electrons and HI atoms often contribute togeter

- C^+ cooling
  - ◇ C^+: $1s^2\ 2s^2\ 1p$
    - ▲ Spin orbit coupling leads to fine structure levels
    - ▲ $2p_{\frac{1}{2}}$, $2p_{\frac{3}{2}}$
  - ◇ Energy: $\Delta E = 92$K

$$e^- + C^+(2P_{\frac{1}{2}}) \rightarrow e^- + C^+(2P_{\frac{3}{2}}) \tag{19}$$

$$\gamma^e_{jk} = \frac{g_k}{g_j}\gamma^e_{kj}\exp\left(\frac{-E_{jk}}{kT}\right) \tag{20}$$

$$= \frac{8.63\times10^{-6}\Omega(j,k)}{g_k T^{\frac{1}{2}}} \tag{21}$$

  - ◇ Consider only e^- collisions
    - ▲ Pseudo emissivity

$$E_{jk}\gamma^e_{jk} = \frac{7.9\times10^{-20}}{T^{\frac{1}{2}}}\exp(-92\text{K}/T) \tag{22}$$

    - ▲ Cooling rate

$$\Lambda^e_{C^+} = n_e n_{C^+} E_{jk}\gamma^e_{jk} \tag{23}$$

    - ▲ Again

$$n_{C^+} = \frac{\text{C}}{\text{H}} n_H d_C \tag{24}$$

    - ▲ Therefore

$$\frac{\Lambda^e_{C^+}}{n_H^2} = \frac{7.9\times10^{-20}}{T^{\frac{1}{2}}} x \frac{\text{C}}{\text{H}} d_C \exp(-92\text{K}/T) \tag{25}$$

  - ◇ Allowing for HI collisions and taking $C/H = 4\times10^{-4}$

$$\frac{\Lambda_{C^+}}{n_H^2} = \left[3.2\times10^{-23}x + 2.5\times10^{-27}(1-x)\right] d_C \frac{\exp(-92\text{K}/T)}{T^{\frac{1}{2}}} \tag{26}$$

- There is fine structure cooling from OI and SiII too (in warmer gas)
  - ◇ $E_{jk}(\text{Si}^+) = 287$K
  - ◇ $E_{jk}(\text{O}^0) = 158$ and 227K

D. Cooling in HI Regions: Lyα

- Collisional excitation of Lyα leads to cooling
- Important for gas at $T > 10^4$K

- Standard expression

$$\Lambda_{\mathrm{Ly}\alpha} = n_e n_H \left[<\sigma_{1s,2s} v> + <\sigma_{1s,2p} v> \right] \frac{3}{4} h\nu_0 \tag{27}$$

- Rates
  - ◇ The 1s→2s rate is only about half 1s→2p
  - ◇ Expression

$$<\sigma_{1s2p} v> \approx 3.23 \times 10^{-10} T^{\frac{1}{2}} \left(1 - \frac{1.75 \times 10^4}{T}\right) \exp\left(\frac{-11.8 \times 10^4 \mathrm{K}}{T}\right) \tag{28}$$

E. Spitzer Model

- Equate C^+ heating with C^+ cooling to estimate ISM temperature
- Assume collisions are dominated by HI
- Equating..

$$\frac{\Gamma}{n_H^2} = \frac{\Lambda}{n_H^2} \tag{29}$$

$$(1.2\mathrm{eV}) \left(\frac{\mathrm{C}}{\mathrm{H}} d_C\right)^2 \frac{1.4 \times 10^{-10}}{T^{0.6}} = \frac{2.5 \times 10^{-27} d_C \exp(-92\mathrm{K}/T)}{T^{\frac{1}{2}}} \tag{30}$$

$$9 \times 10^{-3} \left(\frac{d_C}{0.5}\right) = \exp(-92\mathrm{K}/T) \tag{31}$$

$$T = 20\mathrm{K} \tag{32}$$

- This value is much lower than the T inferred from 21cm studies ($\sim$ 100K)
- What went wrong?
  - ◇ Overestimate of cooling rate?
  - ◇ Additional heating source?

F. Electron Density in HI Regions of the ISM

- General
  - ◇ Examine attenuation of Pulsar radiation
  - ◇ Measure 'Dispersion Measure' and distance to determine n_e
- Faraday rotation
  - ◇ Consider the e^- response to a plane wave
  - ◇ Treat the electrons as a fluid
  - ◇ EM radiation drives a current which modifies the incident radiation field

- Ignoring a magnetic field, the frequency of the plane wave becomes

$$\omega^2 = \omega_p^2 + c^2k^2 \tag{33}$$
$$\omega_p^2 \equiv \frac{4\pi n_e e^2}{m_e} \tag{34}$$

- Index of refraction

$$m \equiv \frac{c}{v_p} = \left[1 - \frac{\omega_p^2}{\omega^2}\right]^{\frac{1}{2}} \tag{35}$$

- Can measure radiation over a frequency range to determine ω_p and then n_e

- Observe pulsars
  (a) $\omega < \omega_p$
    - $\mathrm{Re}(m) = 0$
    - No propagation of the radiation!
    - For $n_e = 0.03 - 0.1\,\mathrm{cm}^{-3}$, $\omega_p = 10^4\mathrm{Hz}$
    - Why doesn't the wave propagate?
      - ▲ Debye Radius

$$4\pi n_e \mathrm{e}^2 R_D^2 \sim kT \tag{36}$$
$$\omega_p^2 m_e R_D^2 \sim kT \tag{37}$$
$$\omega_p^2 R_D^2 \sim \frac{kT}{m_e} \tag{38}$$

      - ▲ Let $v_T^2 = kT/m_e$

$$\frac{1}{\omega_p} \sim \frac{R_D}{v_T} \tag{39}$$

      - ▲ If $\omega < \omega_p$, then e^- can travel fast enough to 'cancel' out the propagating wave!

  (b) $\omega > \omega_p$
    - Each pulse has a wide spectrum of frequencies
    - Pulse delays will occur as a function of ω
    - Group velocity

$$v_g = \frac{d\omega}{dk} = c\left[1 - \frac{\omega_p^2}{\omega^2}\right]^{\frac{1}{2}} \tag{40}$$
$$\approx c\left(1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}\right) \tag{41}$$

    - Pulse arrival time
      - ▲ Lower $\omega \Rightarrow$ longer time

$$\mathcal{T}(\omega) = \int_0^L \frac{ds}{v_g(\omega)} \approx \frac{L}{c} + \frac{1}{2c}\int_0^L ds \frac{\omega_p^2}{\omega^2} \tag{42}$$

- ▲ Take measurements at a wide range of ω
- ▲ Evaluate

$$\frac{\mathcal{T}(\omega)}{d(1/\omega^2)} = \frac{1}{2}\int_0^L ds \frac{\omega_p^2}{c} = \frac{1}{2}\left(\frac{4\pi e^2}{m_e c}\right)\int_0^L n_e ds \tag{43}$$

- ◇ Define DM, the Dispersion measure

$$\text{DM} = \int n_e ds \quad (\text{pc}\,\text{cm}^{-3}) \tag{44}$$

$$\frac{\mathcal{T}(\omega)}{d(1/\omega^2)} = 1.63 \times 10^{17}\,\text{DM} \tag{45}$$

- ◇ Difficult part
  - ▲ Measure L for the pulsar
  - ▲ Use 21cm + spiral arms

- Answer

$$<n_e>= 0.03\,\text{cm}^{-3} \tag{46}$$

  - ◇ Compare with Spitzer's estimate
  - ◇ Assumed all e^-'s came from C

$$n_e = n_C = \frac{\text{C}}{\text{H}} n_H \tag{47}$$

$$= 10^{-4} n_H = 0.0001\,\text{cm}^{-3} \tag{48}$$

- Puzzle
  - ◇ What leads to the extra source of electrons?
  - ◇ Is it related to 'missing' heating?

G. Cosmic Rays

- Origin
  - ◇ 1MeV protons
  - ◇ Accelerated by shocks from expanding supernova remnants
  - ◇ Via magnetic fields
- Ionization

$$\zeta_H \equiv \text{Ionization per target per atom per sec} \tag{49}$$

  - ◇ Include secondary ionizations from energetic electrons
  - ◇ i.e. CR + $2H^0 \to e^- + H^+ + H^0 \to 2H^+$
- Ionization equilibrium

$$n_{\text{HI}}\zeta_H = n_e n_p \alpha_B \tag{50}$$

$$n_e = n_p + n_i \tag{51}$$

- ◇ n_i = Electrons from ionization of metals
- ◇ Solve for n_p

$$n_p = \frac{-\alpha_B n_i + \alpha_B n_i \left[1 + \frac{4n_{\rm HI}\zeta_H}{\alpha_B n_i^2}\right]^{\frac{1}{2}}}{2\alpha_B} \tag{52}$$

$$= \frac{n_i}{2}\left[\sqrt{1 + \frac{4n_{\rm HI}\zeta_H}{\alpha_B n_i^2}} - 1\right] \tag{53}$$

- Cosmic ray spectrum
  - ◇ Not well determined
    - ▲ Area of active research
  - ◇ Rough estimate
  - ◇ Adopt

$$\zeta_H = 7 \times 10^{-18}{\rm s}^{-1} \ \text{ at E} \sim 1\text{MeV} \tag{54}$$

- Electron density
  - ◇ Evaluate n_p, n_e for the WNM ($T \sim 6000$K)

$$n_p \approx \sqrt{\frac{n_H \zeta_H}{\alpha_B}} = \sqrt{\frac{7 \times 10^{18} n_{HI}}{4 \times 10^{-13}}} \tag{55}$$

$$\approx 4.2 \times 10^{-3}\sqrt{n_{HI}} \tag{56}$$

$$n_e = n_p + n_i = n_H \left[\frac{n_p}{n_H} + \frac{n_i}{n_H}\right] \tag{57}$$

$$= n_H \left[\frac{4.2 \times 10^{-3}}{n_H^{\frac{1}{2}}} + 5 \times 10^{-4}\right] \tag{58}$$

- ◇ Altogether..

$$\frac{n_e}{n_H} \sim (1-4)\% \tag{59}$$

  - ▲ Much larger than the value Spitzer assumed in the 1940's

- Cosmic Ray Heating

$$\Gamma_{CR} = n_H \zeta_H <E> \tag{60}$$

  - ◇ In addition to ionizing the gas, the CR will dump K.E. into the ISM
  - ◇ Average Energy
    - ▲ $<E>$ of the CR $\sim 10^9$eV/particle
    - ▲ Transferred energy is small
    - ▲ The $\vec{E}$ vector of the cosmic ray passing the HI atom is like a delta function
    - ▲ The absorbing co-efficient has $a \propto \omega^{-3}$
    - ▲ This is very strongly peaked so the energy is never more than a few Ryd

Table 1: Energy transfer

$< E >$	β_{CR}	E_{CR}
35eV	0.05	1.1 MeV
50eV	0.95	2 GeV

    - ▲ Furthermore, only a fraction of the electron energy goes into HI heating
      (a) Share it energy with other free electrons
      (b) Excite Lyα
      (c) Ionize other HI atoms
    - ▲ Bottom line

$$< E > \sim 7\,\text{eV} \tag{61}$$

  - ◇ Cross-section with ISM

$$\sigma_{ion}(\beta) = \frac{1.23 \times 10^{-20}}{\beta^2}\left[6.20 + \log\frac{\beta^2}{\sqrt{1-\beta^2}} - 0.43\beta^2\right] \tag{62}$$

$$\beta = v/c \tag{63}$$

$$\zeta_{CR} = \int n_{CR}(E)\sigma_{ion}(E)\beta c dE \quad (\text{s}^{-1}) \tag{64}$$

    - ▲ Density: $n_{CR}(E) \propto KE^{-\gamma} \quad \gamma = 2.5$
  - ◇ Can CR heat the ISM by themselves?
    - ▲ To match $T = 80$K, require $\zeta_H = 6 \times 10^{-16}\text{s}^{-1}$
    - ▲ This is 10× our extrapolated value
    - ▲ The rate is so high, the observed abundance of CI is inconsistent
    - ▲ Perhaps this is not the whole story!

H. Photo-electric Heating

- Process
  - ◇ UV photon strikes a PAH or dust grain
  - ◇ An electron is kicked off with $E \sim$ few eV
  - ◇ It shares its K.E. with the surrounding gas via collisions
- Heating rate
  - ◇ Consider grains with size a and charge state i
  - ◇ These will have ionization energies $h\nu_i(a)$
  - ◇ Let $E_{kin}(a,i)$ by the average energy per ionization
  - ◇ Let σ_{grain} be the ionization cross-section

$$n\Gamma_{\rm pe} = \int_{a_-}^{a_+} da n(a) \sum_i \int_{\nu_i(a)}^{13.6{\rm eV/h}} n_\nu \sigma_{grain}(\nu) E_{kin}(a,i) d\nu \tag{65}$$

- Grain contributions to heating
  - ◇ Adopt a power-law size distribution for PAHs and grains
  - ◇ About half of the heating comes from small grains ($a < 15$Å)
  - ◇ The other half comes from grains with $a = 15 - 100$Å
- Heating effeciency
  - ◇ As with heating by photoionization of atoms (C,H), the heating rate will ultimately depend on the recombination rate of electrons with grains and PAHs
  - ◇ For photo-electric heating, this is parameterized by the 'charging parameter' γ

$$\gamma \equiv \frac{G_0 T^{\frac{1}{2}}}{n_e} \tag{66}$$

  - ◇ Express the heating rate in terms of an efficiency factor ϵ

$$n\Gamma_{pe} = 10^{-24} \epsilon n G_0 \ \ {\rm erg\, cm^{-3}\, s^{-1}} \tag{67}$$

    - ▲ The heating efficiency ϵ is a sensitive function of γ
    - ▲ See Tielens, Fig 3.4
    - ▲ It reaches a maximum value of ≈ 0.05 in dense gas
- Heating of the CNM
  - ◇ Heating by photoionization is

$$n\Gamma_{\rm C+} \approx \ \times 10^{-29} G_0 n \ \ {\rm erg\, cm^{-3}\, s^{-1}} \tag{68}$$

  - ◇ Heating by the photo-electric effect

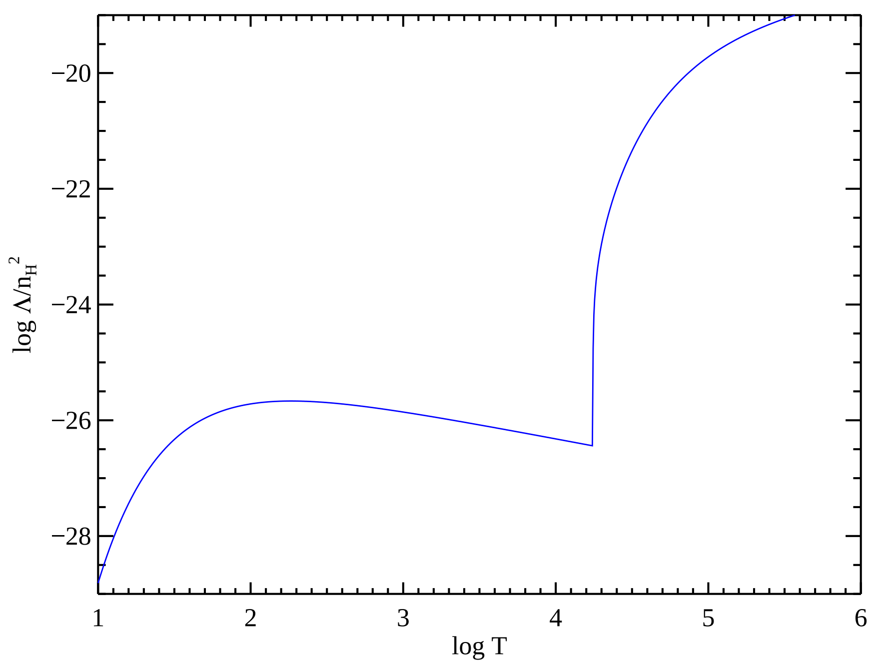
$$n\Gamma_{pe} \approx \ \times 10^{-26} G_0 n \ \ {\rm erg\, cm^{-3}\, s^{-1}} \tag{69}$$

▲ This is much larger because there are many more PAH targets than C^0

▲ This is enough to maintain the CNM at 80K !!

I. 2 Phase Model

- Cooling curve



- Express
  - ◇ Cooling is a 2-body process

$$\Lambda = n_H^2 f(T) \tag{70}$$

  - ◇ Heating is a 1 body process

$$\Gamma_H = n_H \mathcal{H} \tag{71}$$

▲ $\mathcal{H}$ is the ionization rate

▲ $\mathcal{H}$ is independent of T

- Thermal equilibrium

$$f(T) = \frac{\mathcal{H}}{n_H} \tag{72}$$

  - ◇ Holding all other parameters fixed, express

$$T = T(n_H) \tag{73}$$

  - ◇ Increasing $n_H \Rightarrow T$ decreases
- Examine T along the cooling curve

(a) Consider the 'plateau' along Λ

- ◇ 100K $< T <$ 10000K
- ◇ T is very sensitive to n_H

(b) Above the plateau ($T \gtrsim 10^4$K)

- ◇ Λ increases by orders of magnitude for T increasing from 10^4K
- ◇ This drives the gas toward $T \approx 10^4$K

(c) Below the plateau ($T \lesssim 100$K)

- ◇ Λ decreases expoentially for $T < 100$K
- ◇ T holds at $\approx 10^2$K

◇ Fig

▲ The intermediate region is unstable to perturbations

- Net loss function (Qualitative treatment)

$$\Gamma - \Lambda = -\rho\mathcal{L} \tag{74}$$

(a) Consider a blob that to 0th order is in Thermal Equilibrium ($\mathcal{L} = 0$)

(b) Perturb the blob away from T.E. along an isobar: P =const= ρT

◇ Pressure equilibrium is upheld in the ISM

$$t_S = \frac{L}{c_S} \ll t_{instability} \tag{75}$$

◇ Fig of T vs. ρ with $\mathcal{L}$

$$\mathcal{L} = \frac{\Lambda - \Gamma}{\rho} \tag{76}$$

- ◇ Phase F
  - ▲ Lower T, raise ρ
    - ∘ $\mathcal{L} < 0 \Rightarrow$ Heating exceeds cooling
    - ∘ Blob returns to equilibrium
  - ▲ Raise T, lower ρ
    - ∘ $\mathcal{L} > 0 \Rightarrow$ Cooling exceeds heating
    - ∘ Also, back to T.E.
  - ▲ Stable phase
- ◇ Phase H
  - ▲ Similar story
  - ▲ Stable phase
- ◇ Phase G
  - ▲ Lower T, raise ρ
    - ∘ $\mathcal{L} > 0 \Rightarrow$ Cooling $\Rightarrow T \downarrow$ further
    - ∘ Unstable
  - ▲ Raise T, lower ρ
    - ∘ $\mathcal{L} < 0 \Rightarrow$ heating $\Rightarrow T \uparrow$ further
    - ∘ Unstable
  - ▲ Unstable phase

- Quantitative perturbation theory
  - ◇ Criteria for instability

$$\mathcal{L} = \frac{1}{\rho}\left(\Lambda - \Gamma\right) = \frac{1}{\rho}\left(n_H^2 f(T) - n_H \mathcal{H}\right) \tag{77}$$

  - ▲ Introduce

$$X \equiv \frac{\rho_H}{\rho} = \frac{m_H n_H}{\rho} \tag{78}$$

$$\Rightarrow n_H = \frac{X}{m_H}\rho \tag{79}$$

  - ▲ Substitute

$$\mathcal{L} = \frac{1}{\rho}\left(\frac{X}{m_H}\right)^2 \rho^2 f(T) - \frac{1}{\rho}\left(\frac{X}{m_H}\right)\rho\mathcal{H} \tag{80}$$

$$= \rho g(T) - \mathcal{H}' \tag{81}$$

$$g(T) \equiv \left(\frac{X}{m_H}\right)^2 f(T) \tag{82}$$

$$\mathcal{H}' \equiv \left(\frac{X}{m_H}\right)\mathcal{H} \tag{83}$$

▲ Therefore

$$\mathcal{L} = \mathcal{L}(\rho, T) \tag{84}$$

◇ Perturb ρ, T

$$T = T_E + \delta T \tag{85}$$

$$\rho = \rho_E + \delta\rho \tag{86}$$

▲ Isobar

$$P = \rho T \rightarrow \delta P = \rho\delta T + T\delta\rho = 0 \tag{87}$$

$$\delta\rho = \frac{-\rho}{T}\delta T \tag{88}$$

◇ Perturb $\mathcal{L}$

$$(\,\delta\mathcal{L}\,)_P = \left(\frac{\delta\mathcal{L}}{\delta T}\right)_P \delta T + \left(\frac{\delta\mathcal{L}}{\delta\rho}\right)_T \delta\rho \tag{89}$$

$$\left(\frac{\delta\mathcal{L}}{\delta T}\right)_P = \left(\frac{\delta\mathcal{L}}{\delta T}\right)_\rho - \left(\frac{\rho}{T}\right)_E \left(\frac{\delta\mathcal{L}}{\delta\rho}\right)_T \tag{90}$$

◇ Instability

$$\left(\frac{\delta\mathcal{L}}{\delta T}\right)_P < 0 \tag{91}$$

◇ Recalling our definition of $\mathcal{L}$ (Equation 80)

$$\left(\frac{\delta\mathcal{L}}{\delta\rho}\right)_T = g, \quad \left(\frac{\delta\mathcal{L}}{\delta T}\right)_\rho = \frac{dg}{dT} \tag{92}$$

$$\rho\frac{dg}{dT} - \frac{\rho}{T}g < 0 \tag{93}$$

$$\frac{d\ln g}{d\ln T} < 1 \tag{94}$$

- Reexamine the cooling curve

◇ Prediction: 2 phases in pressure equilibrium

(a) Warm gas with $T = 10^4$K (WNM)

(b) Cold gas with $T = 10^2$K (CNM)

◇ Fig

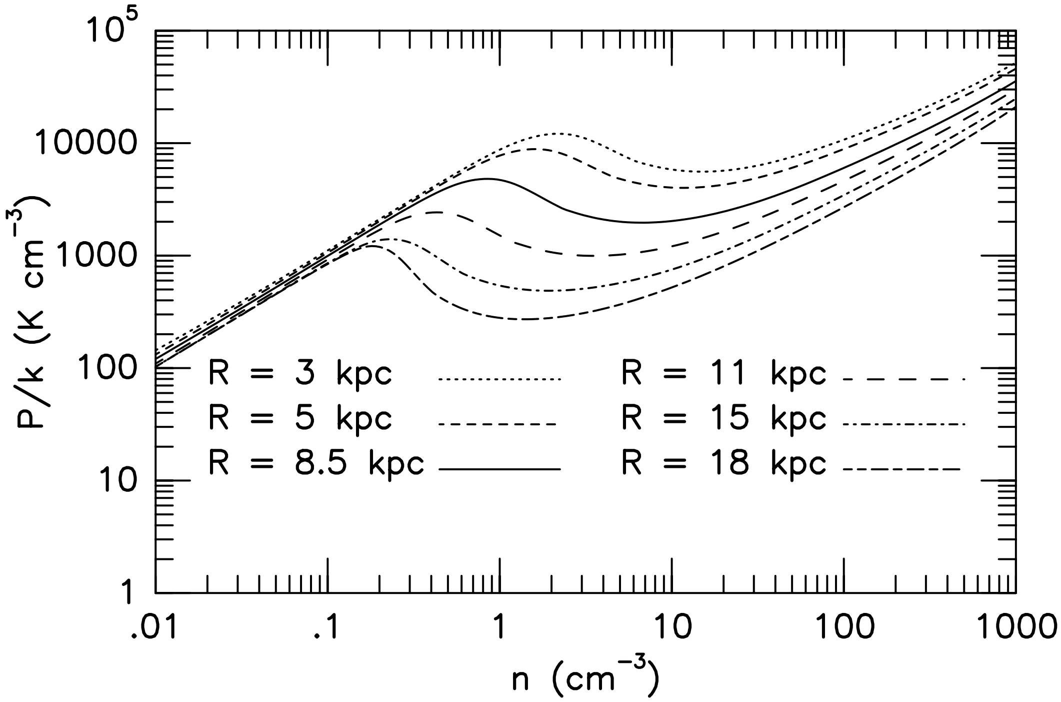
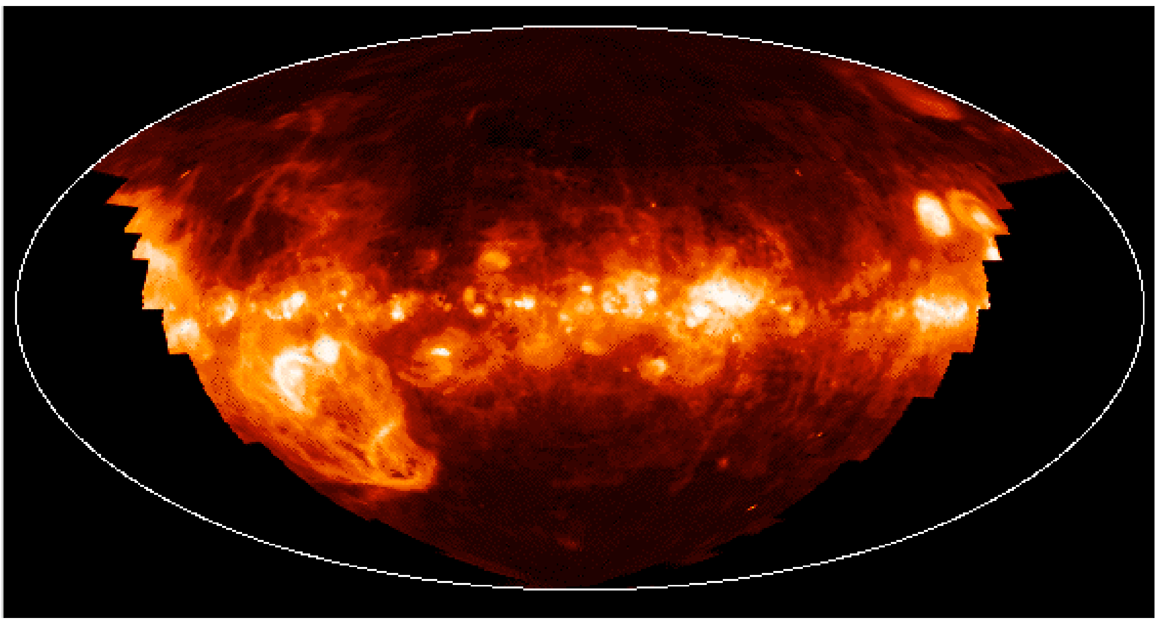


FIG. 7.—Phase diagrams showing thermal pressure P/k vs. hydrogen nucleus density n at Galactocentric radii $R = 3$, 5, 8.5, 11, 15, and 18 kpc. Curves apply to the WNM/CNM boundary at a depth of 1×10^{19} cm^{-2} through the WNM. Gas is thermally stable to isobaric perturbations where $dP/dn > 0$.

- Problems with this simple picture
  - (a) Pervasive WNM is not observed
    - ◇ WNM is almost as clumpy as the CNM
    - ◇ Impossible to maintain pressure equilibrium
  - (b) Pervasive WIM in the ISM
    - ◇ Hα experiments show the presence of a widespread WIM
    - ◇ How do we accomodate it within the 2-phase model?

J. 3 Phase Model

- Violent ISM
  - ◇ Shock waves
  - ◇ As always, astrophysics is more complicated than we think
  - ◇ Akin to weather
- Supernova (SN) remnants
  - ◇ In calculating the SN rate, Cox noted that the remnants overlap
  - ◇ Estimated the 'porosity' was high
    - ▲ f_V is the volume filling factor
    - ▲ $f_V \sim 0.1$



- McKee and Ostriker
  - ◇ Argued Cox underestimated f_V
  - ◇ Estimated $f_V \sim 1$
- SN – Source of additional heat in the CNM
  - ◇ Produces a WIM that is in pressure equilibrium with the WNM+CNM
  - ◇ This medium is observed in Hα emission
- Physical processes of the 3-phase ISM
  - (a) Mass exchange between the phases
    - ◇ Evaporation of the CNM, WNM
  - (b) Pressure equilibrium holds
  - (c) Thermal pressure $\propto$ SNR
- Problems solved

- ◇ Explains the 200pc layer of HI clouds
  - ▲ Dissipation (cloud collisions) tends to shrink the layer
  - ▲ Need mechanical energy to keep this layer
- ◇ Temperature of the CNM
- ◇ Clumpiness of the WNM
- ◇ Existance of the WIM