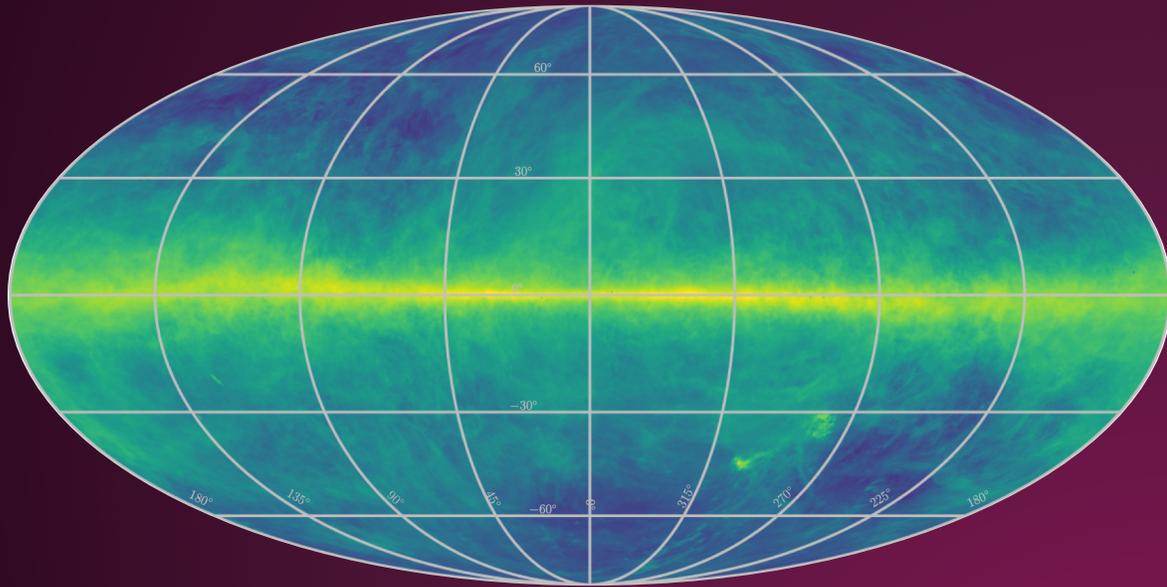# Heating and cooling processes and the two-phase neutral media
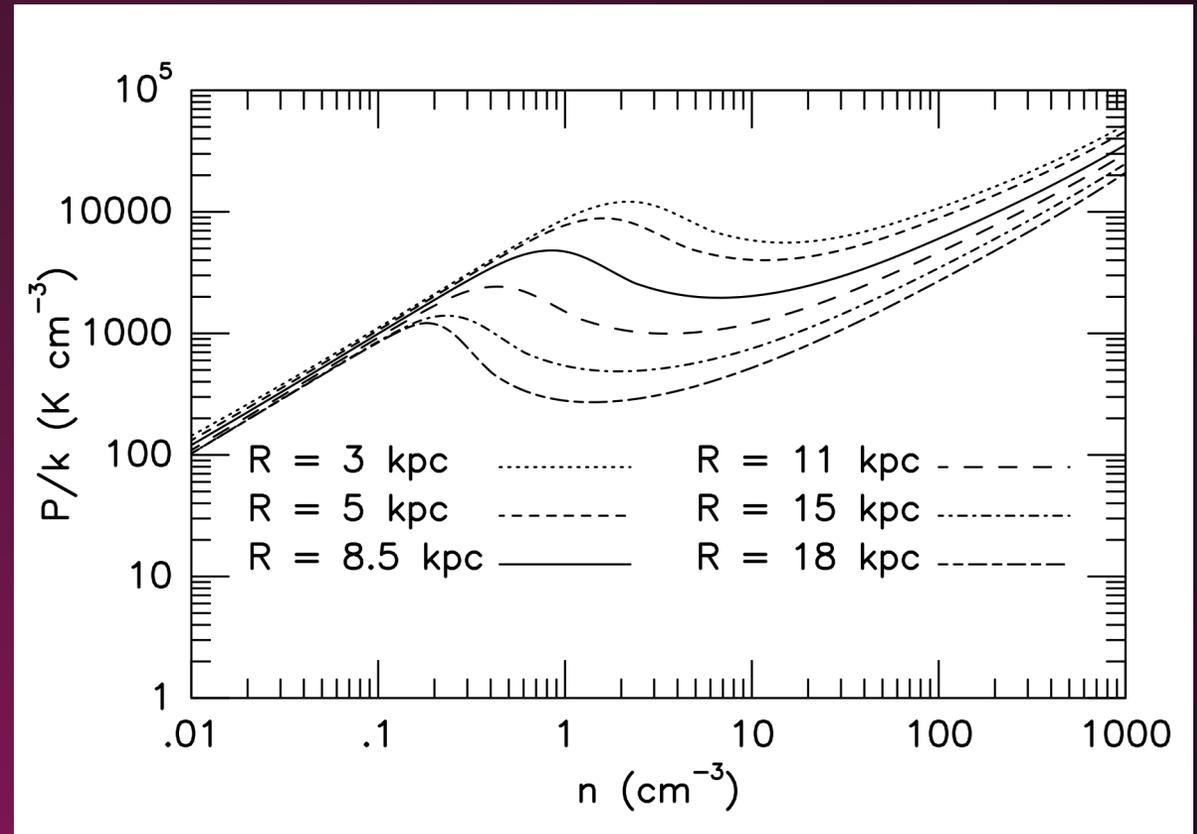
HI4PI collaboration et al. 2016

ASTR 605

Joe Burchett

9/27/2021

Wolfire et al. 2003

Overview

- Most of the MW disk ISM is neutral
  - ~78% of neutral material is atomic (H I)

- We are interested in states where the gas is in thermal equilibrium
  - Must balance heating (Γ) and cooling (Λ)

- Result: two equilibrium temperatures/densities
  - Cold neutral medium (CNM):   ~100 K
 - Warm neutral medium (WNM):   few x 1000 K

Heating processes

- Cosmic ray ionization → H, He, and metals

- X-rays → ionization of H & He

- UV from stars { Ionization of dust grains / Ionization of metals } photoionization (photoelectric heating)

- Shocks (supernovae, etc.)

Γ

Cosmic rays

- Protons, electrons, and other ions

- Moving at nonthermal velocities
  - High energy particles (> 1 Mev!)

- Plenty of energy to ionize species → free electrons
  - Mean kinetic energy <KE> = 35 ev
  - "secondary" ionizations - rate ~ 0.67 per primary ionization
  - Excitations of atoms, ions, and molecules
  - Add thermal energy to gas
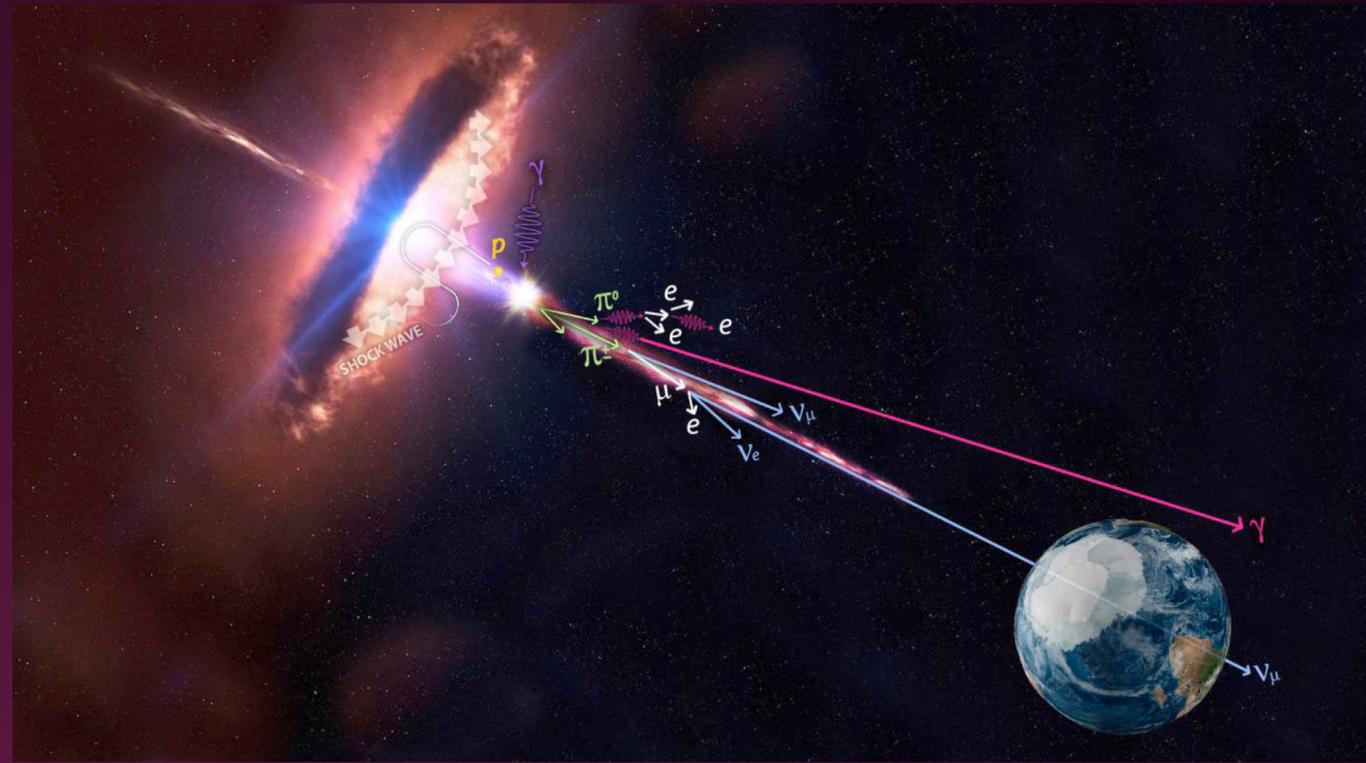
IceCube/NASA

Cosmic ray ionization

Secondary ionization rate:

$$\phi_s(\mathrm{CR}) \approx \left(1 - \frac{x_e}{1.2}\right) \frac{0.67}{1 + (x_e/0.05)}$$
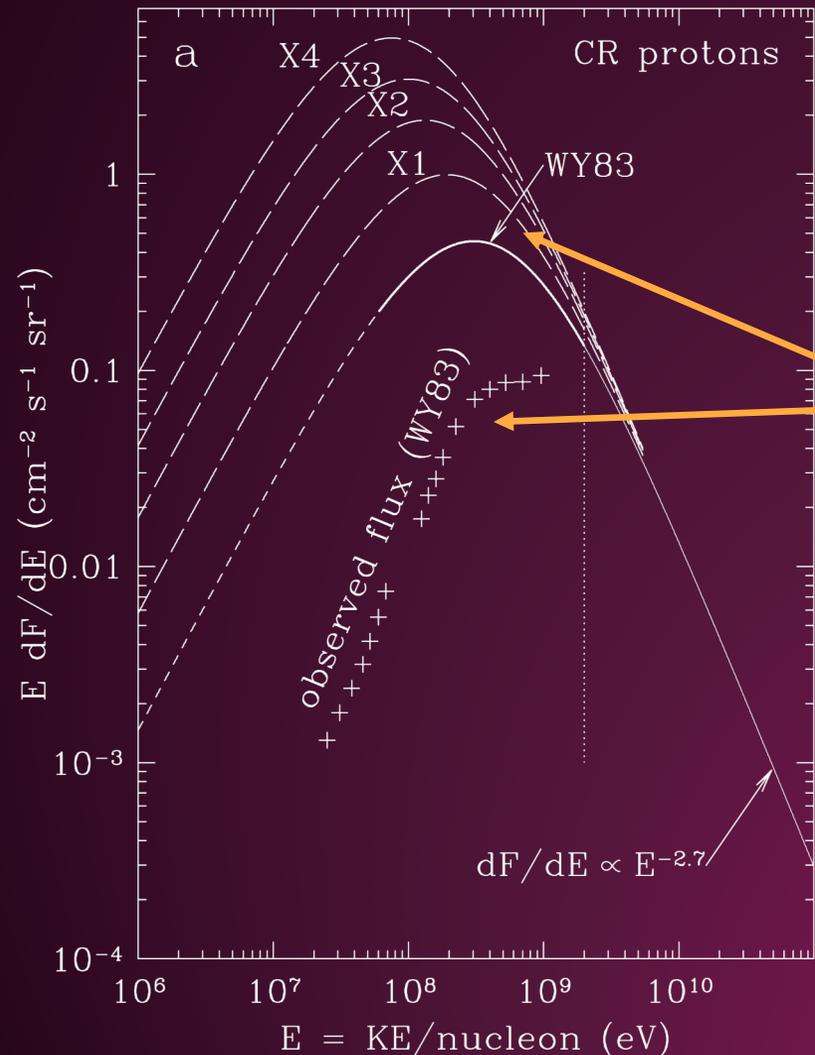
Production rate of free electrons:

$$\left(\frac{dn_e}{dt}\right)_{\mathrm{CR}} \approx 1.1 n_{\mathrm{H}} \zeta_{\mathrm{CR}} \left(1 - \frac{x_e}{1.2}\right) [1 + \phi_s(\mathrm{CR})]$$

Primary ionization rate:

$$\zeta_{\mathrm{CR}} = 4\pi \int_{E_{\min}}^{\infty} \sigma_{\mathrm{ci}}(E) E \frac{dF}{dE} \cdot \frac{dE}{E}$$

Cosmic ray ionization rates

Flux spectrum of cosmic rays
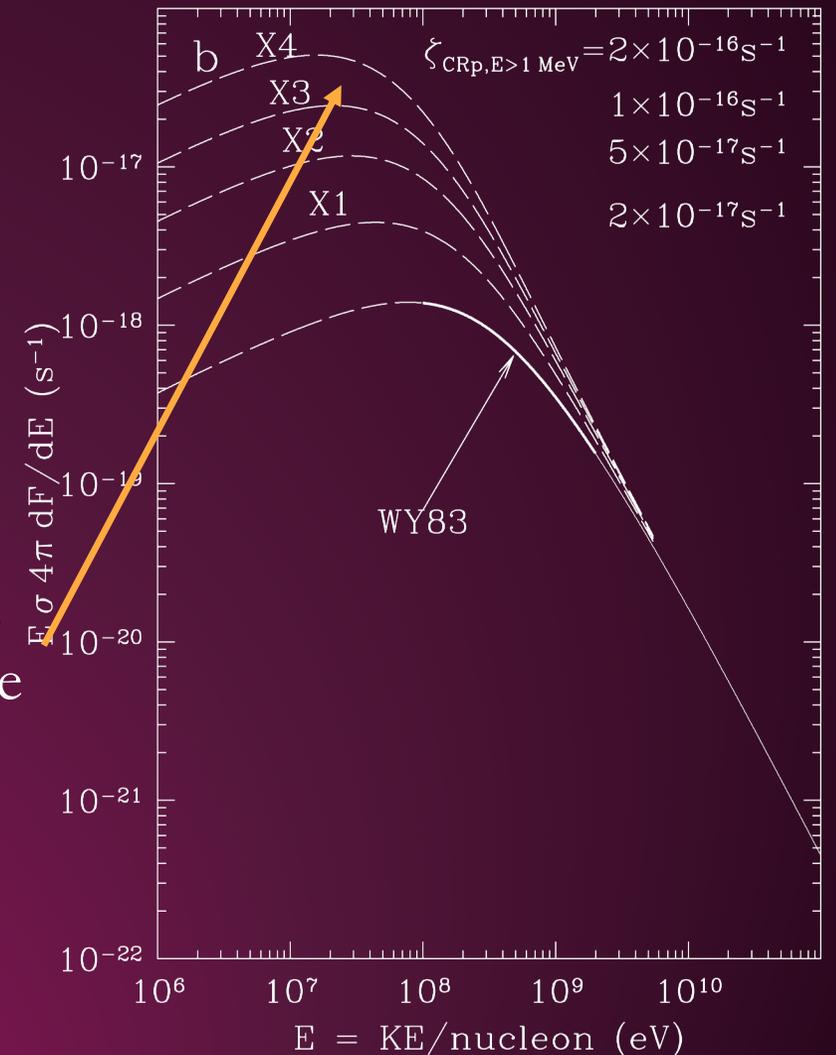(per CR energy)

Primary ionization rate
(per CR energy)

The Voyager probe measured
the cosmic ray spectrum
(Webber & Yushak 1983)

Corrections for the solar wind
cause large uncertainties
at < 2 GeV

Chemistry in molecular clouds
indicates primary ionization rate
$\zeta_{CR,P} \sim 2$ x 10^{-16} s^{-1}

Fun fact: Bill Webber was
faculty in our department!

Cosmic rays in the ISM context

When ionization is high
  - Electron loses energy via Coulomb interactions with other free electrons
  - 100% thermalization

When ionization is low (mostly neutral)
  - Fraction of electron kinetic energy that is thermalized: ~0.2

ionization
fraction

Under partial ionization:

Heat per primary ionization: $E_h \approx 6.5 \, \text{eV} + 26.4 \, \text{eV} \left(\dfrac{x_e}{x_e + 0.07} \right)^{1/2}$, $x_e \equiv \dfrac{n_e}{n_{\text{H}}}$

Volumetric heating rate from neutrals: $\Gamma_{\text{CR},n} \approx \left[n(\text{H}^0) + n(\text{He}^0) \right] \zeta_{\text{CR}} E_h$

Cosmic ray electron heating: $\Gamma_{\text{CR},e} \approx A \, \zeta_{\text{CR}} \, n_e$ (A ~ 4.6 x 10^{-10} erg)

Photoelectric heating - Dust

Grains can be photoionized by photons down to hν ~ 4.5 eV

UV electrons from stars
- Possibly an order of magnitude more abundant than cosmic rays!

Photoionization heating rate per unit volume:

$$\frac{\Gamma_{pe}}{n_H} \approx 1.4 \times 10^{-26} \frac{erg}{s} \left[\frac{n(8-13.6\,eV)}{3 \times 10^{-3}\,cm^{-3}} \right] \frac{\langle \sigma_{abs} \rangle}{10^{-21}\,cm^2} \frac{\langle Y \rangle}{0.1} \frac{(\langle E_{pe} \rangle - \langle E_c \rangle)}{1\,eV}$$

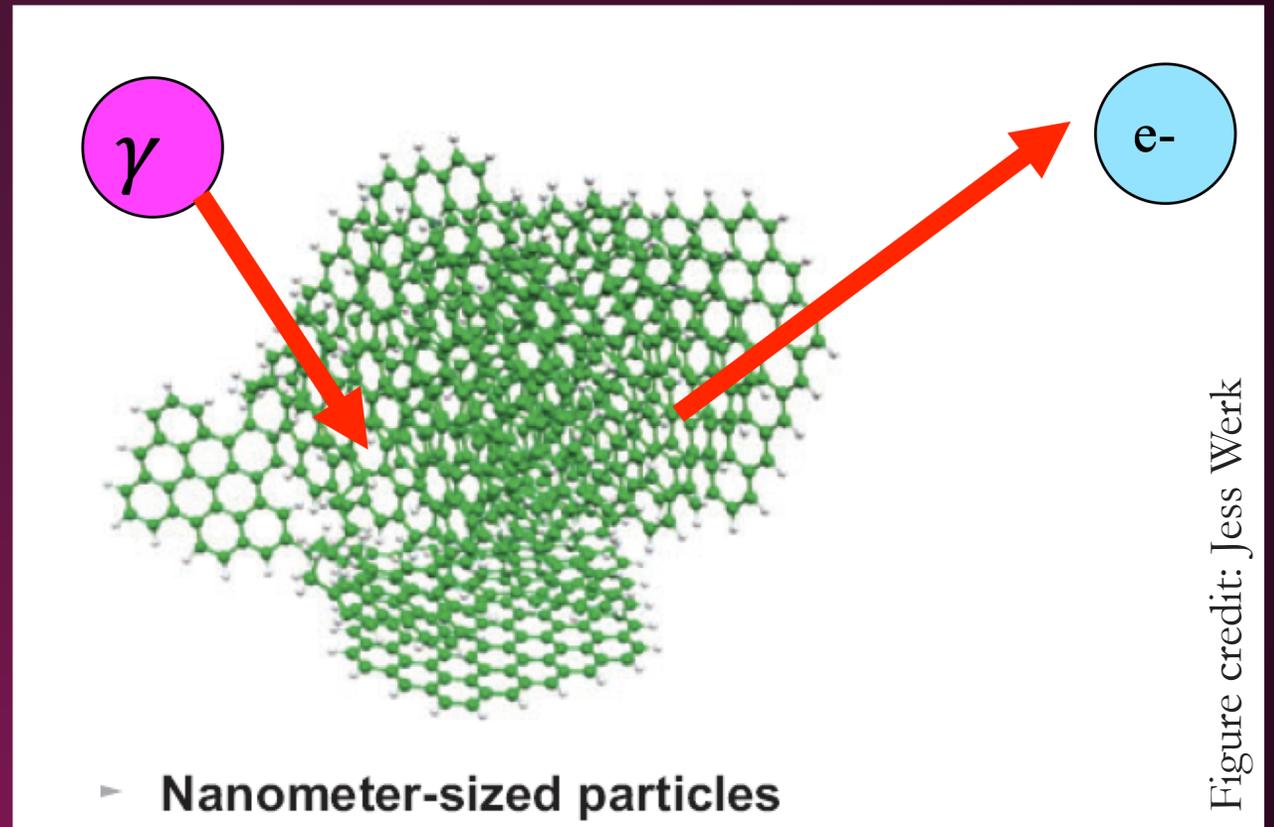Heating from photoionization of dust grains dominates in neutral ISM!

γ   e-

▶ **Nanometer-sized particles**
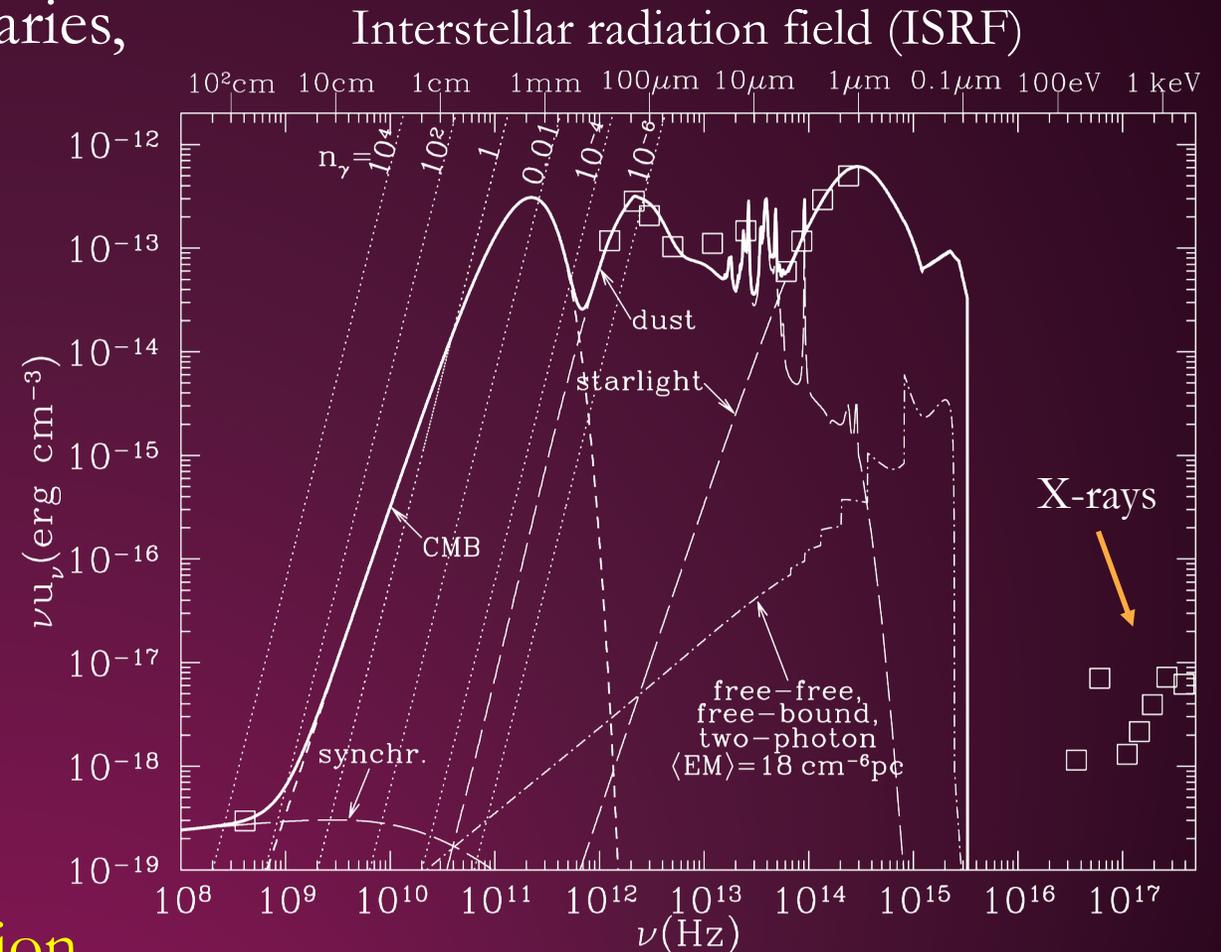
Photoelectric heating due to X-rays

- X-rays originate from hot plasma, X-ray binaries, & black holes

- Operates on H, He, and metals

- Some ionization heating from 0.4 eV photons from the ISRF

- Mostly important near strong < 200 eV X-ray sources

- Lower heating contribution than CR ionization

Interstellar radiation field (ISRF)

Photonionization of metals by starlight

Element		I→II
1	H	13.5984
2	He	24.5874
3	Li	5.3917
4	Be	9.3227
5	B	8.2980
6	C	11.2603
7	N	14.5341
8	O	13.6181
9	F	17.4228
10	Ne	21.5645
11	Na	5.1391
12	Mg	7.6462
13	Al	5.9858
14	Si	8.1517
15	P	10.4867
16	S	10.3600
17	Cl	12.9676
18	Ar	15.7596
19	K	4.3407
20	Ca	6.1132
21	Sc	6.5615
22	Ti	6.8281
23	V	6.7462
24	Cr	6.7665
25	Mn	7.4340
26	Fe	7.9024

Note: nearly all photons w/ $h\nu > 13.6$ eV will be "used up"

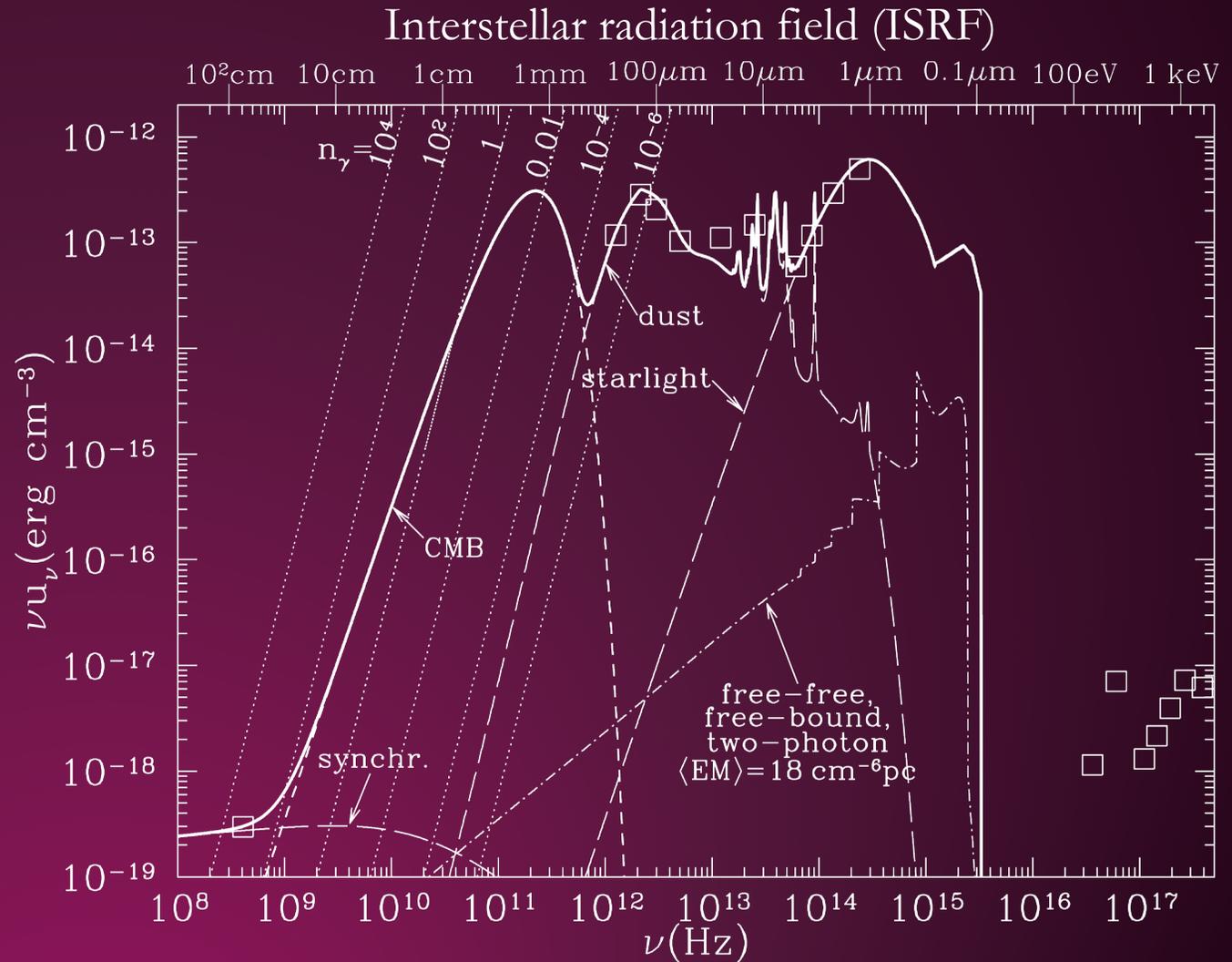- Why?

Dominated by ionization of neutral carbon: C I → C II

$\Gamma_C \sim 4 \times 10^{-28}$ erg s^{-1} cm^{-3}

Heating mechanism negligible in the diffuse ISM*

* However, ionization important for cooling

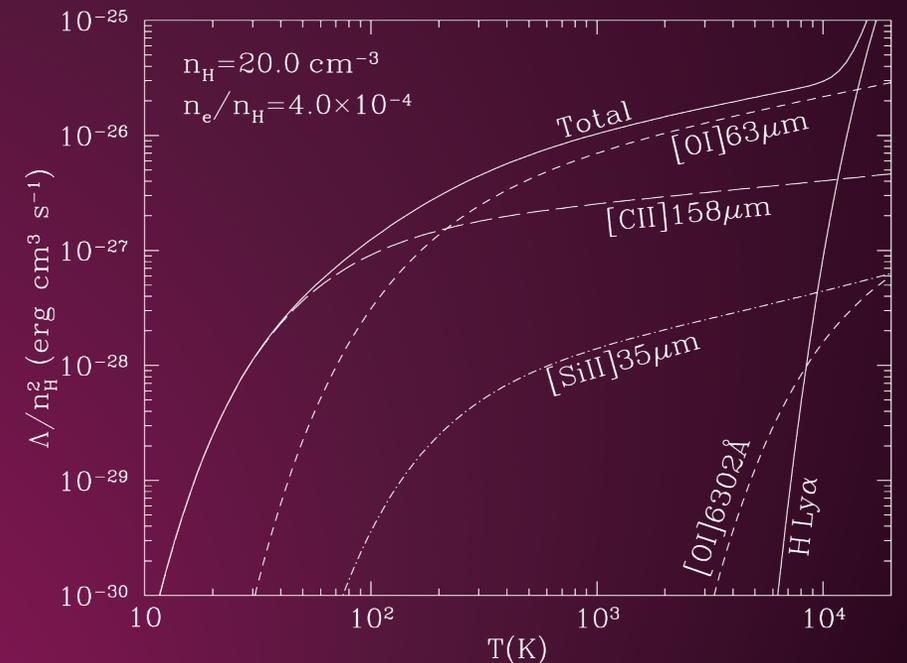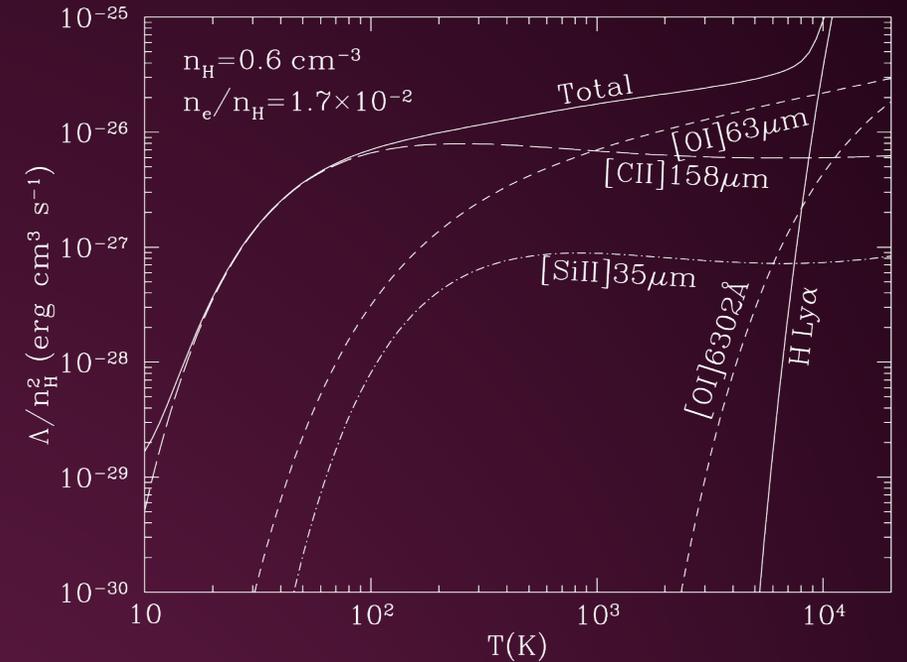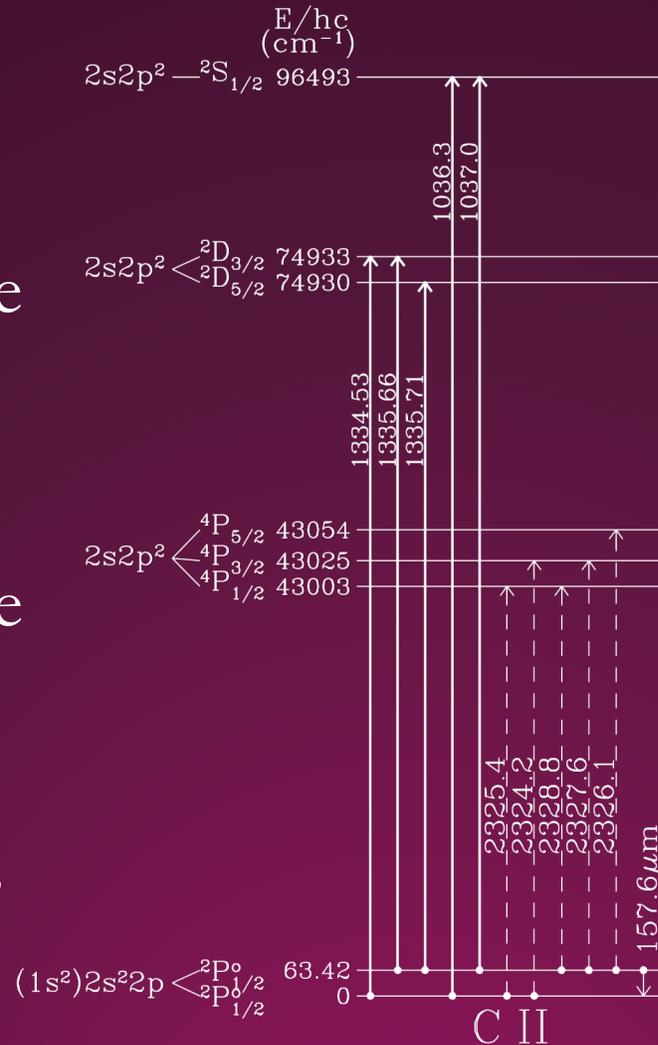Interstellar radiation field (ISRF)

Cooling

Dominated by radiative cooling from low-ions of metals
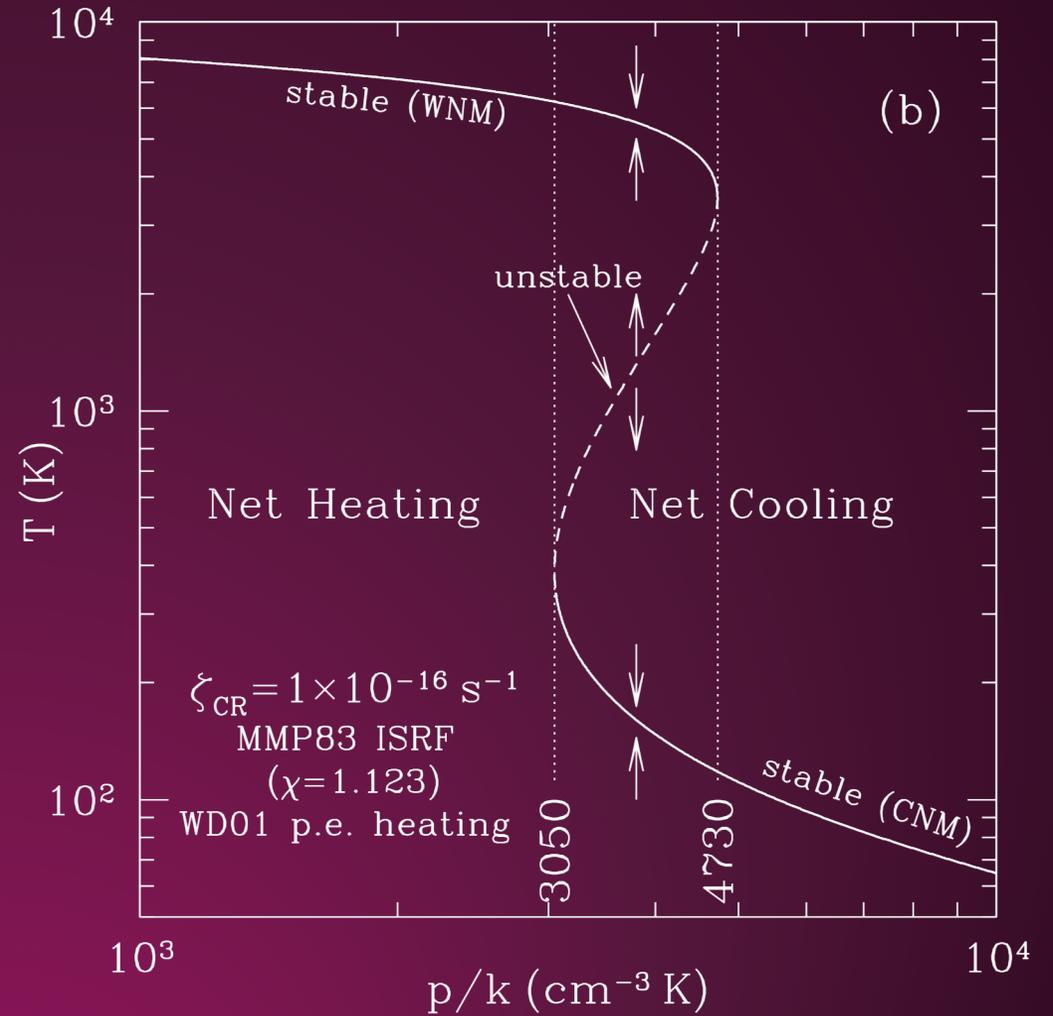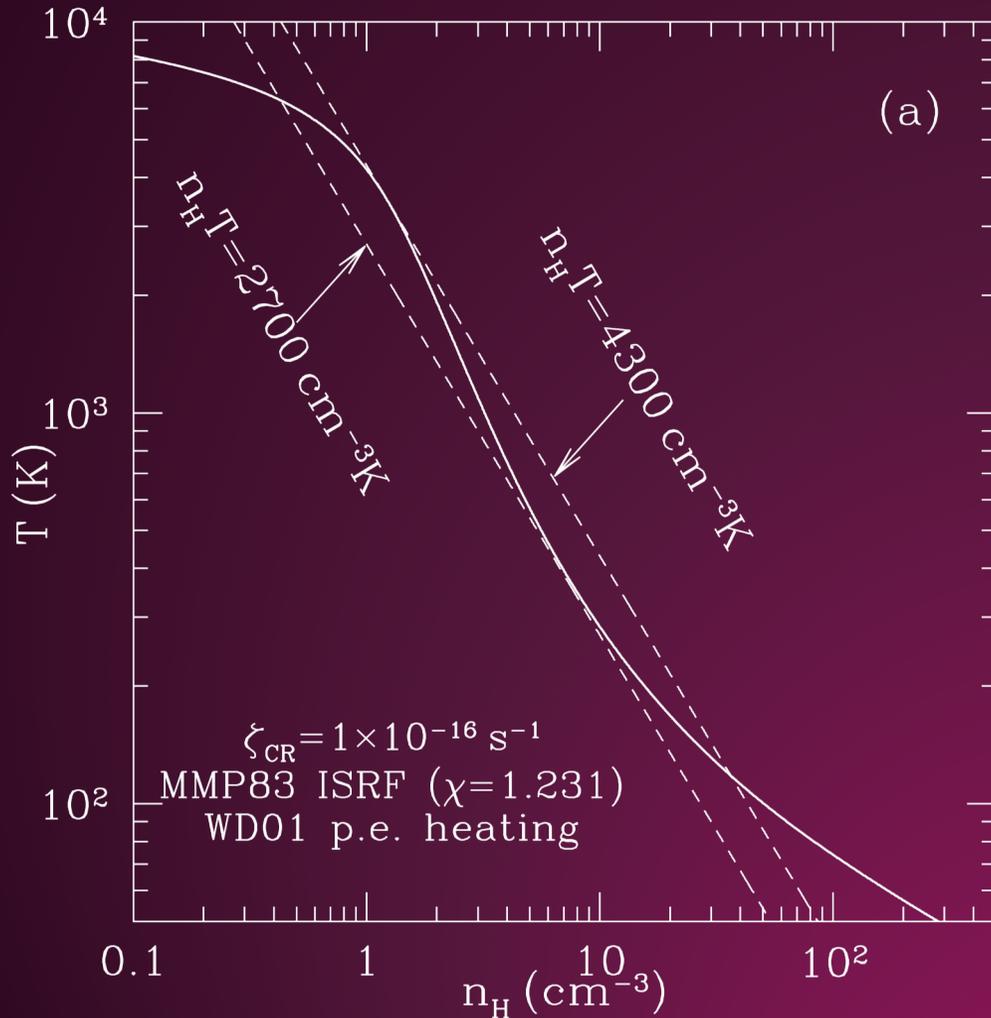
- At Far-IR wavelengths

[C II] dominant among these

Why [C II]?

- Almost all C in CII at these temperatures

- At low temperatures only fine structure energy levels populated

Two phase model of the neutral ISM

Balance $\Lambda(T) = \Gamma$

Two phase model of the neutral ISM
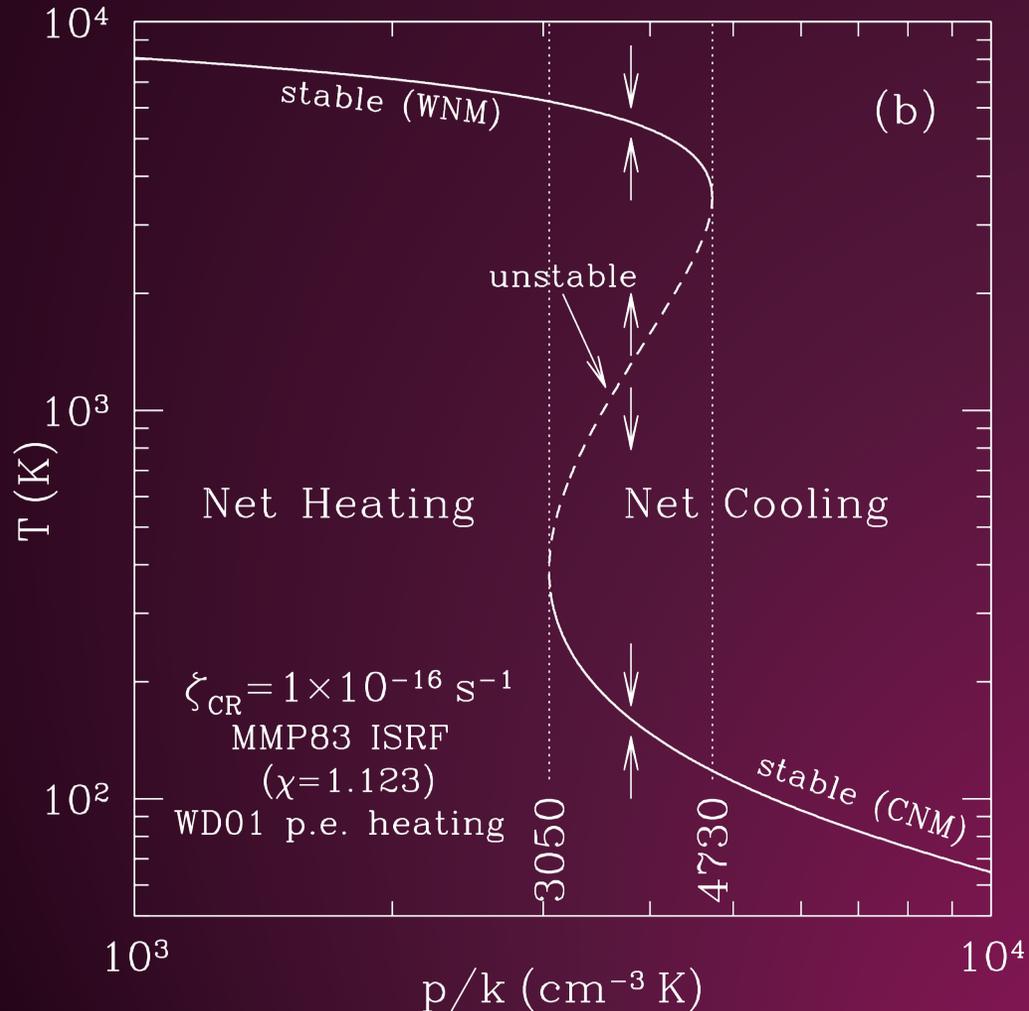
Table 30.1 Conditions at Stable Thermal Equilibria for $p/k = 3800\,\mathrm{cm}^{-3}\,\mathrm{K}$

	CNM	WNM
$T\,(\mathrm{K})$	160.	5512
$n_\mathrm{H}\,(\mathrm{cm}^{-3})$	21.5	0.626
$n_e\,(\mathrm{cm}^{-3})$	0.00925	0.0116
n_e/n_H	0.00043	0.0185
$n(\mathrm{H}^+)/n_\mathrm{H}$	0.000272	0.0167
$4\pi\nu j_\nu(\mathrm{dust},100\,\mu\mathrm{m})/n_\mathrm{H}\ (10^{-26}\,\mathrm{erg\,s^{-1}H^{-1}})$	240.	240.
$4\pi j/n_\mathrm{H}\ (10^{-26}\,\mathrm{erg\,s^{-1}H^{-1}})$: [C II]$158\,\mu\mathrm{m}$	2.85	0.385
[O I]$63.2\,\mu\mathrm{m}$	2.00	1.05
[O I]$145\,\mu\mathrm{m}$	0.119	0.0875
[O I]$6302\,\text{Å}$	—	0.0317
[Si II]$34.8\,\mu\mathrm{m}$	0.0341	0.0474
[S II]$6733\,\text{Å}$	—	0.100
[S II]$6718\,\text{Å}$	—	0.148
[Fe II]$5.34\,\mu\mathrm{m}$	—	0.0216
[Fe II]$26.0\,\mu\mathrm{m}$	0.00101	0.00904

Two phase model in galactic context
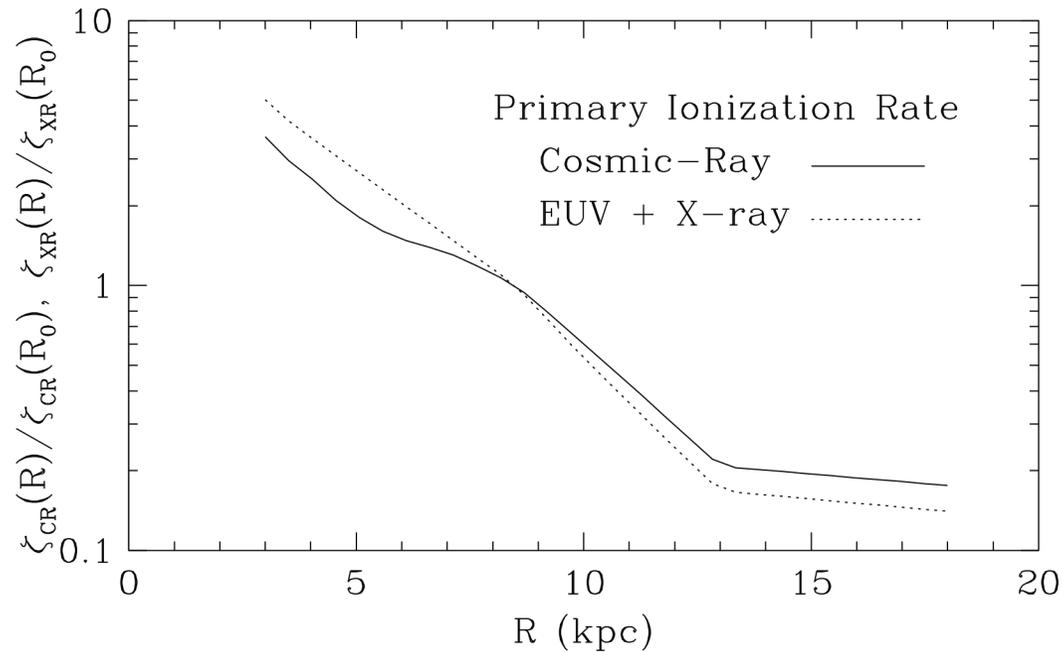
FIG. 6.—Primary cosmic-ray (*solid curve*) and EUV plus X-ray (*dotted curve*) ionization rates vs. Galactocentric radius R normalized to the value at $R = R_0$. At $R = R_0$ the primary cosmic-ray ionization rate is taken to be $\zeta_{CR}(R_0) = 1.8 \times 10^{-17}$ cm^{-3} s^{-1}. The EUV and X-ray rate depends on the adopted value of the WNM cloud column, N_{cl}. For $N_{cl} = 1.0 \times 10^{20}$ cm^{-2}, $\zeta_{XR}(R_0) = 8.9 \times 10^{-19}$ s^{-1}; for $N_{cl} = 1.0 \times 10^{19}$ cm^{-2}, $\zeta_{XR}(R_0) = 1.6 \times 10^{-17}$ s^{-1}; for $N_{cl} = 3.0 \times 10^{18}$ cm^{-2}, $\zeta_{XR}(R_0) = 7.6 \times 10^{-17}$ s^{-1}. Note that the EUV and X-ray rate always exceeds the cosmic-ray rate because of the effects of secondary ionizations. Typical values for N_{cl} are of order 10^{19} cm^{-2}.
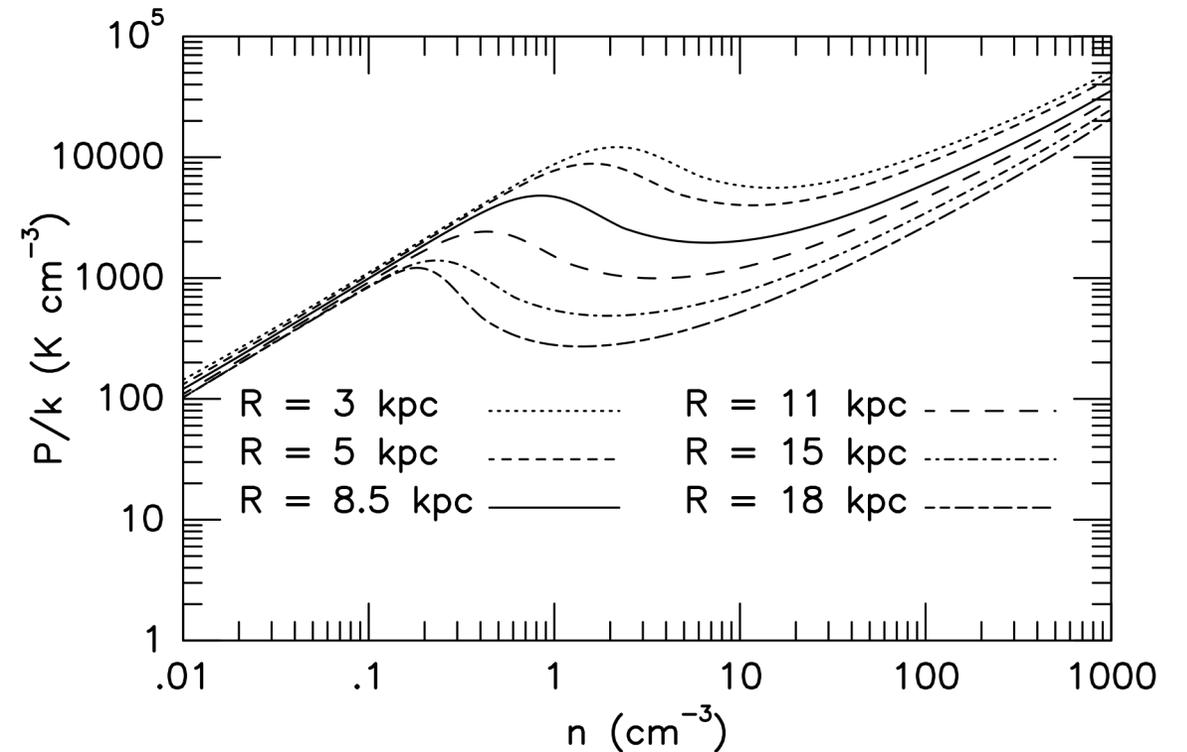
FIG. 7.—Phase diagrams showing thermal pressure P/k vs. hydrogen nucleus density n at Galactocentric radii $R = 3, 5, 8.5, 11, 15,$ and 18 kpc. Curves apply to the WNM/CNM boundary at a depth of 1×10^{19} cm^{-2} through the WNM. Gas is thermally stable to isobaric perturbations where $dP/dn > 0$.

Two phase model in galactic context

Different contributions
of heading and cooling

Heating: dashed lines
Heating: solid lines

Wolfire et al. 2003
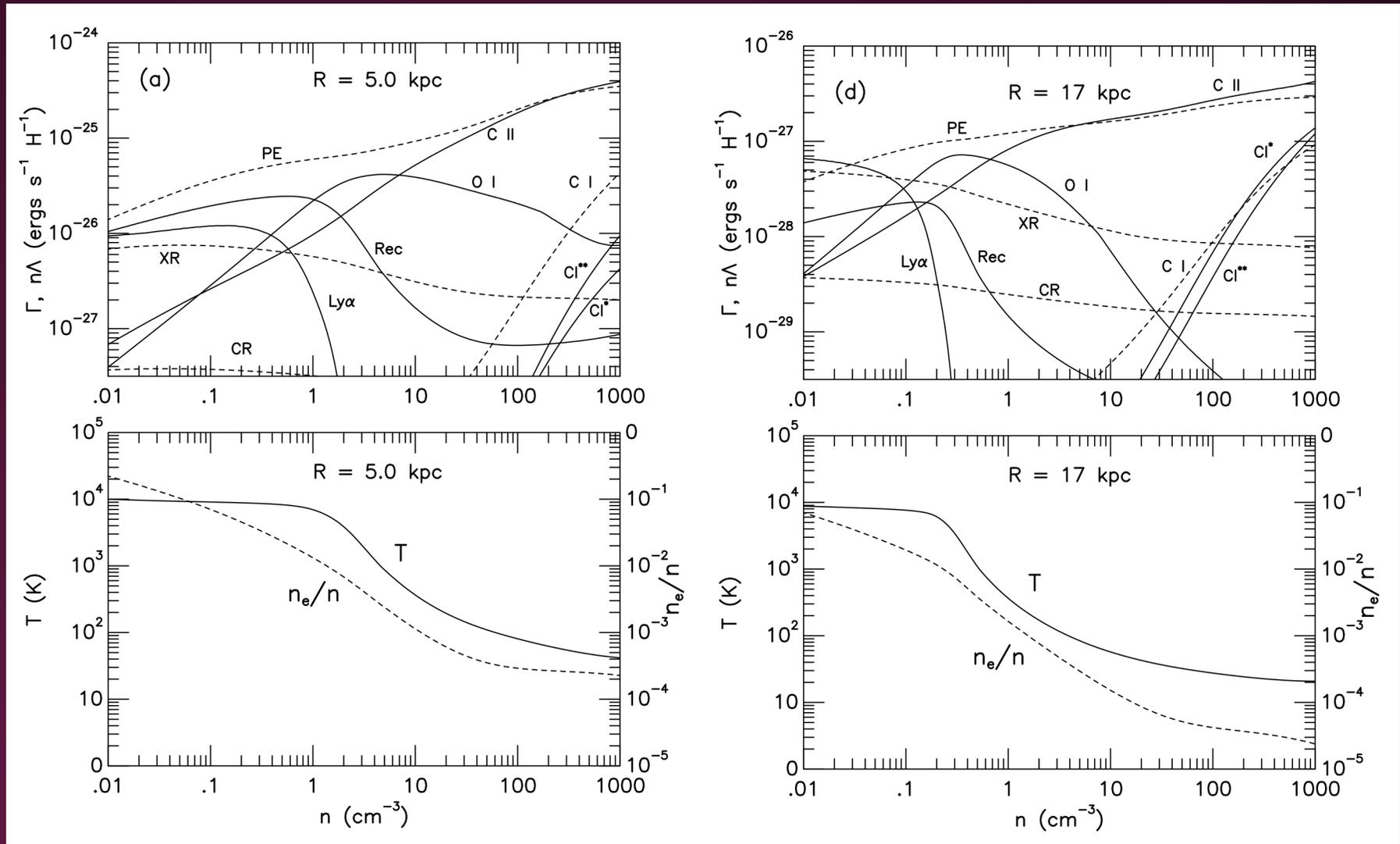
CNM/WNM as a function of gas column density

TABLE 3
RANGE OF PHYSICAL CONDITIONS FOR TWO-PHASE MEDIUM

N_{cl} (cm^{-2})	R (kpc)	$P_{min}/k - P_{max}/k$ (K cm^{-3})	$P_{th,ave}/k$ (K cm^{-3})	WNM T (K)	n (cm^{-3})	T_{ave} (K)	n_{ave} (cm^{-3})	CNM T (K)	n (cm^{-3})	T_{ave} (K)	n_{ave} (cm^{-3})
1×10^{19}	3	5580–12100	8220	8530–5030	0.579–2.17	7960	0.922	345–88.8	14.6–124	124	60.2
	4	4910–10600	7210	8430–4930	0.516–1.93	7880	0.817	323–87.5	13.9–110	121	54.2
	5	4000–8850	5950	8410–4910	0.422–1.63	7880	0.675	312–80.6	11.6–100	111	48.6
	8.5	1960–4810	3070	8310–5040	0.209–0.860	7860	0.349	258–61.6	6.91–71.0	85.0	32.9
	11	995–2420	1550	8130–5080	0.109–0.430	7700	0.180	247–56.5	3.65–39.0	78.4	18.0
	15	487–1400	825	8080–5540	0.0534–0.227	7690	0.0958	229–43.8	1.93–29.0	62.3	12.0
	17	374–1360	713	8190–5690	0.0403–0.215	7800	0.0815	197–35.7	1.72–34.6	51.4	12.6
	18	272–1220	575	8320–6050	0.0287–0.180	7880	0.0648	180–30.7	1.37–36.0	44.1	11.8
1×10^{20}	3	3150–5330	4090	7820–4410	0.359–1.09	7080	0.519	411–136	6.95–35.5	180	20.6
	4	2800–4690	3620	7700–4360	0.325–0.971	6960	0.467	410–133	6.19–32.1	174	18.9
	5	2300–3910	3000	7670–4320	0.268–0.817	6950	0.387	401–122	5.20–29.1	161	17.0
	8.5	1240–2310	1690	7750–4300	0.142–0.485	7150	0.212	324–86.2	3.47–24.4	117	13.2
	11	652–1200	886	7560–4240	0.0770–0.257	6990	0.113	322–77.4	1.84–14.1	106	7.57
	15	329–674	471	7620–4470	0.0385–0.136	7170	0.0588	291–59.6	1.03–10.3	84.6	5.06
	17	253–629	399	7830–5260	0.0287–0.108	7440	0.0480	250–47.3	0.917–12.1	68.2	5.32
	18	179–548	313	8010–5760	0.0198–0.0855	7610	0.0367	223–39.3	0.727–12.7	57.4	4.96
3×10^{18}	3	7340–19900	12100	8800–5370	0.732–3.33	8320	1.29	280–66.6	23.8–271	95.0	115
	4	6490–17300	10600	8700–5260	0.655–2.97	8240	1.15	277–66.1	21.2–238	93.5	103
	5	5290–14500	8770	8670–5560	0.537–2.36	8210	0.950	269–61.9	17.8–214	87.0	91.6
	8.5	2560–7830	4480	8520–5650	0.264–1.25	8100	0.491	233–49.6	10.0–144	69.2	58.9
	11	1300–3940	2260	8330–5380	0.137–0.660	7940	0.253	223–46.0	5.29–77.8	64.3	31.9
	15	635–2300	1210	8240–5910	0.0678–0.349	7860	0.137	194–36.8	2.97–56.7	52.5	20.9
	17	495–2220	1050	8310–6040	0.0521–0.329	7890	0.118	180–31.1	2.50–64.8	44.4	21.5
	18	371–1970	856	8390–6020	0.0385–0.293	7940	0.0953	152–27.5	2.22–65.0	39.1	19.9