Interstellar Medium 2020

Lecture 9: Thermal balance

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Today’s Lecture

- Heating and cooling
- Thermal balance in HII regions
- Thermal balance in the WNM/CNM
- Thermal balance in molecular clouds

Corresponding textbook material: Draine Ch. 27 and 30

Thermal balance equation

In equilibrium:

heating rate [erg cm^{-3} s^{-1}]= cooling rate [erg cm^{-3} s^{-1}]

$$\boxed{\Gamma(T) = \Lambda(T)}$$

Solve → equilibrium kinetic temperature T_{kin}

Heating mechanisms

Radiative heating

- starlight
- radiation from an AGN

Mechanical heating

- shock waves
- dissipation of turbulence

Cosmic ray heating

Gas cooling mechanisms

Cooling by radiation

- Line radiation
  - recombination lines (only in HII regions)
  - collisionally excited lines
- Continuum radiation
  - thermal emission from hot gas
  - NOT: dust emission (why not?)

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Temperatures of HII regions

Central stars of HII regions have a range of temperatures from 20000 to 50000 K.

But HII regions have a much lower and fairly constant temperature: 6000 – 10000 K.

Why?

Thermal balance in HII regions

Heating:

- UV photons from the central star(s)

Cooling:

- Recombination lines
- Free-free emission
- Collisionally excited lines

(dominant mechanisms in red)

Heating in HII regions

$H + h\nu \rightarrow H^{+} + e^{-}$ (similarly for He etc.)

Heating occurs because the e^{-} carries $E_{\mathrm{kin}} = h\,(\nu - \nu_0)$

absorbed photon ionization edge

→ energy converted from stellar radiation into kinetic energy of particles: heating

Heating rate in HII regions

Recall that the photoionization rate in an HII region is

$$\zeta_{\mathrm{pi}} = \int_{\nu_0}^{\infty} n_{\mathrm{HI}} \frac{u_\nu}{h\nu} \sigma_{\mathrm{pi}}(\nu) c \, d\nu$$

Every photoionization adds $E_{\mathrm{kin}} = h\,(\nu - \nu_0)$ to the gas, so the heating rate is

$$\Gamma(T) = \int_{\nu_0}^{\infty} n_{\mathrm{HI}} \frac{u_\nu}{h\nu} \sigma_{\mathrm{pi}}(\nu) c \, h(\nu - \nu_0) \, d\nu = \int_{\nu_0}^{\infty} n_{\mathrm{HI}} u_\nu \frac{\nu - \nu_0}{\nu} \sigma_{\mathrm{pi}}(\nu) c \, d\nu$$

This needs to be evaluated numerically but an approximate expression that can be obtained is $\Gamma(T) = \alpha_B n_p n_e \, \psi \, kT_{\mathrm{c}}$

where $\psi \approx 1$ is a dimensionless number and T_{c} is the colour temperature of the star (see Draine Sect. 27.1).

Cooling rate in HII regions: recombination lines

Every recombination produces multiple photons that escape. The total energy of these photons is equal to the hydrogen ionization potential + the kinetic energy of the captured photon.

So we can write the cooling rate as: $\Lambda_{\mathrm{rr}}(T) = \alpha_B n_p n_e \langle E_{\mathrm{rr}} \rangle$

Here $\langle E_{rr} \rangle$ is the average energy loss per recombination, which again must be calculated numerically, is given approximately by $\langle E_{rr} \rangle = 0.68\ kT_e$ so $\Lambda_{\mathrm{rr}}(T) = \alpha_B n_p n_e (0.68\ kT_{\mathrm{e}})$

Cooling rate in HII regions: free-free cooling

Free-free emission from ionized gas goes at the expense of kinetic energy of the particles → cooling

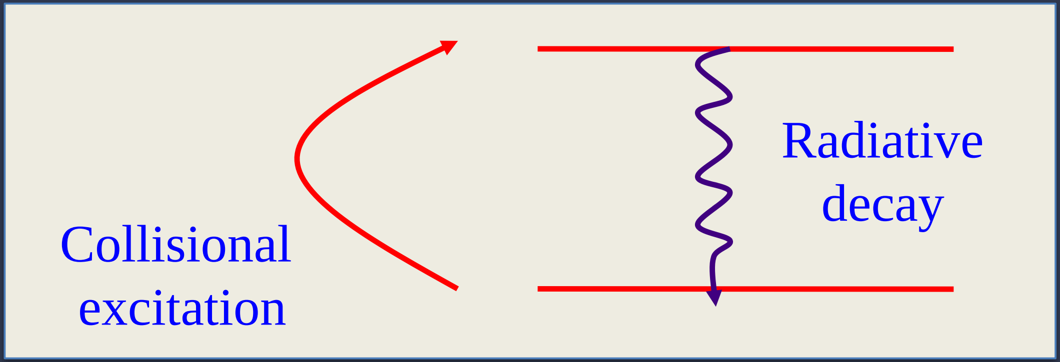
With a similar calculation as before an approximate expression can be derived:

$$\Lambda_{\mathrm{ff}}(T) = \alpha_B n_p n_e (0.54\ kT_e)$$

And the total cooling by recombination lines and free-free emission becomes

$$\Lambda_{\mathrm{ff+rr}}(T) = \alpha_B n_p n_e (1.22\ kT_{\mathrm{e}})$$

Cooling in HII regions: collisionally excited lines



Cooling occurs when collisional excitation is followed by emission of a photon, where the photon can escape.

$A + B \rightarrow A^* + B$

$A^* \rightarrow A + h\nu$

Efficient collisional excitation cooling requires…

- Frequent collisions (density not too low)
- Excitation energy comparable to or less than thermal kinetic energy
- High probability of excitation during collision
- Photon emission before the next collision (density not too high)
- No re-absorption of the photon (low optical depth of gas to line emission)

Collisional excitation cooling in HII regions

Calculating cooling for one line is easy, but for a real HII region:

1. must first solve full photionization equilibrium (including heavy elements)
2. then calculate cooling from every species ([OII], [OIII], [NII], [NIII], [SII], [SIII], etc.)
3. then solve for temperature structure
4. temperature structure affects photoionization equilibrium (for instance, through $\alpha_B(T)$), so this requires iteration

→ numerically computed $\Lambda_{ce}(T)$, which will depend also on density, abundances, and temperature of central star.

Temperatures of HII regions

First consider a metal-free HII region
→ only recombination line and free-free cooling

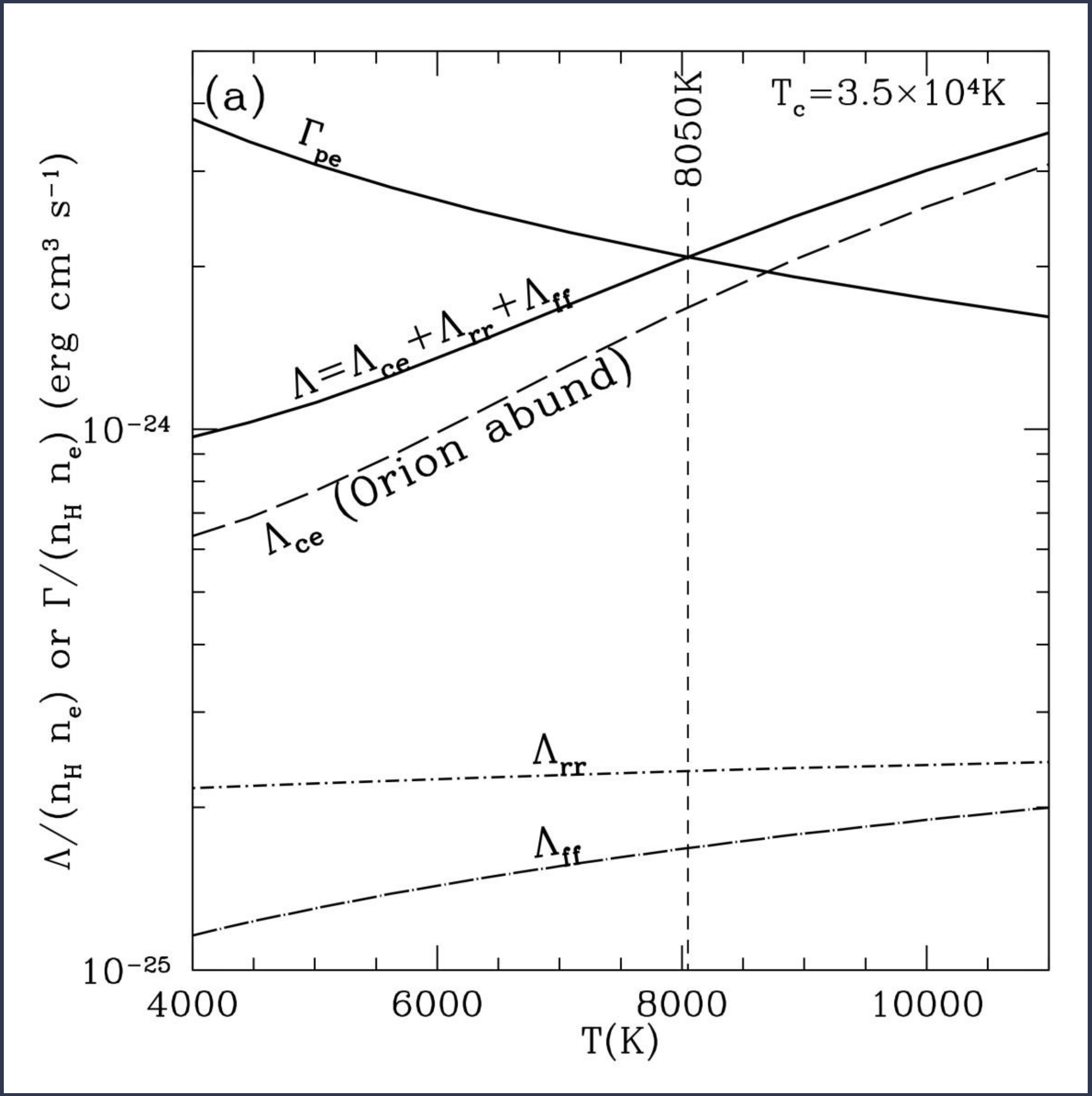
Now $\Gamma_{\mathrm{pi}}(T_e) = \Lambda_{\mathrm{ff+rr}}(T_e)$

so $\alpha_B n_p n_e \psi \, kT_c = \alpha_B n_p n_e (1.22 \, kT_{\mathrm{e}})$

and $T_e = \dfrac{\psi}{1.22} T_c \approx T_c$

This would imply that HII regions have approximately the temperature of their central stars (20000 - 50000 K) but this is not what is observed.
In fact, cooling by collisionally excited lines is the dominant mechanism and including it leads to T_e ~ 6000 - 10000 K.

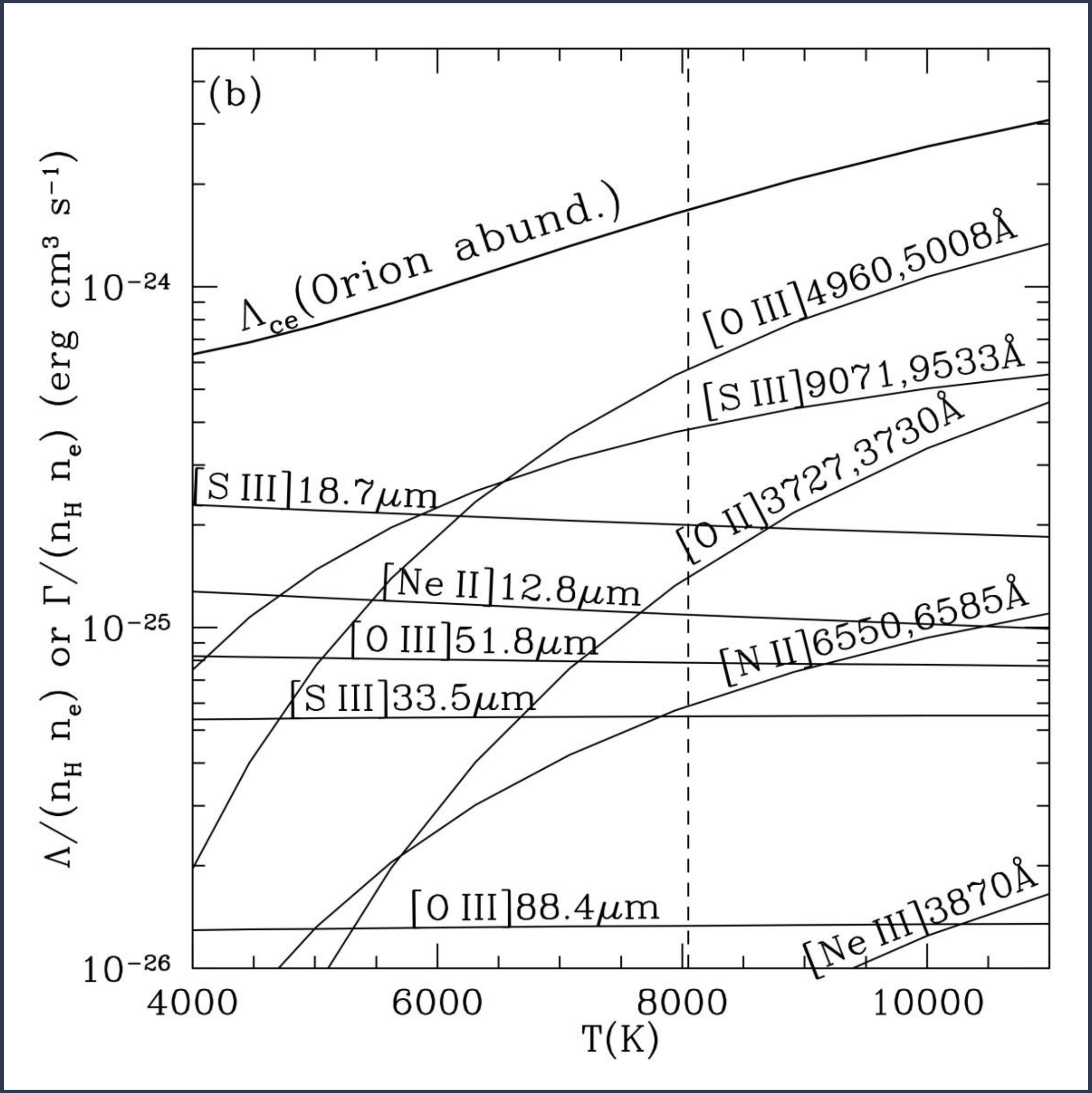
Full thermal balance in an HII region



n_e = 4000 cm^{-3}

(Draine, Fig. 27.1a)

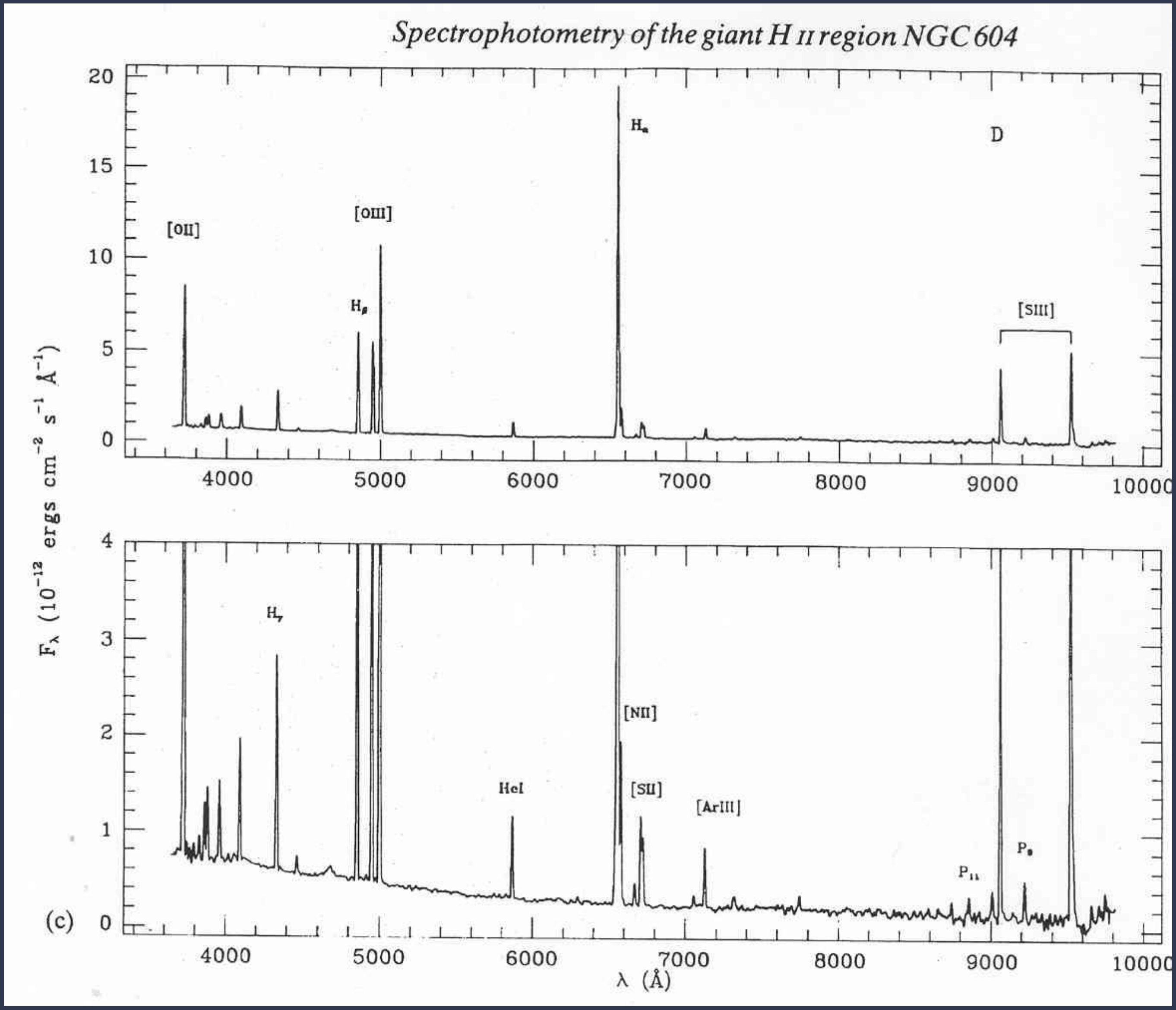
Full thermal balance in an HII region



n_e = 4000 cm^{-3}

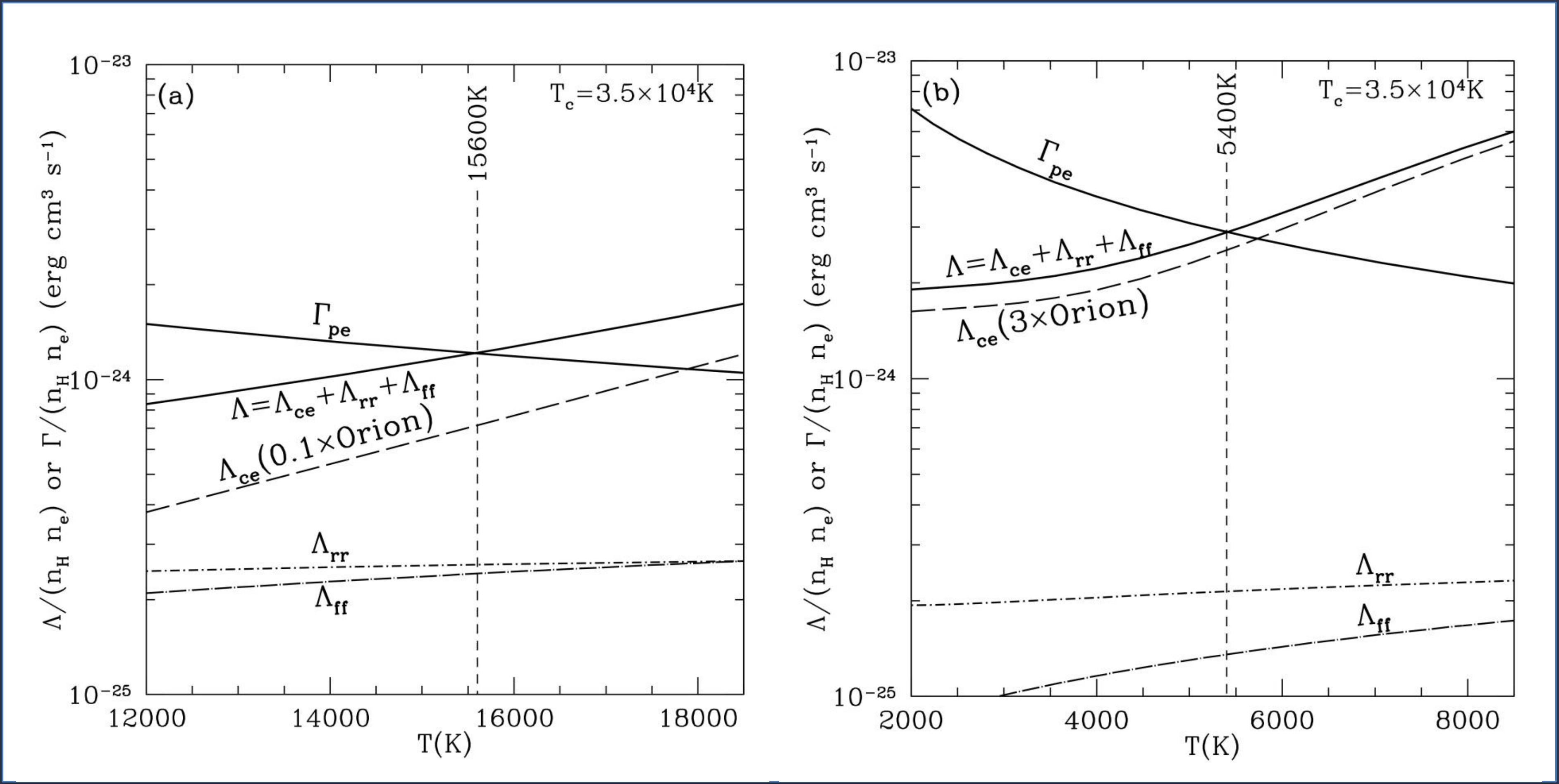
(Draine, Fig. 27.1b)

HII region spectra



Turning the temperature knob

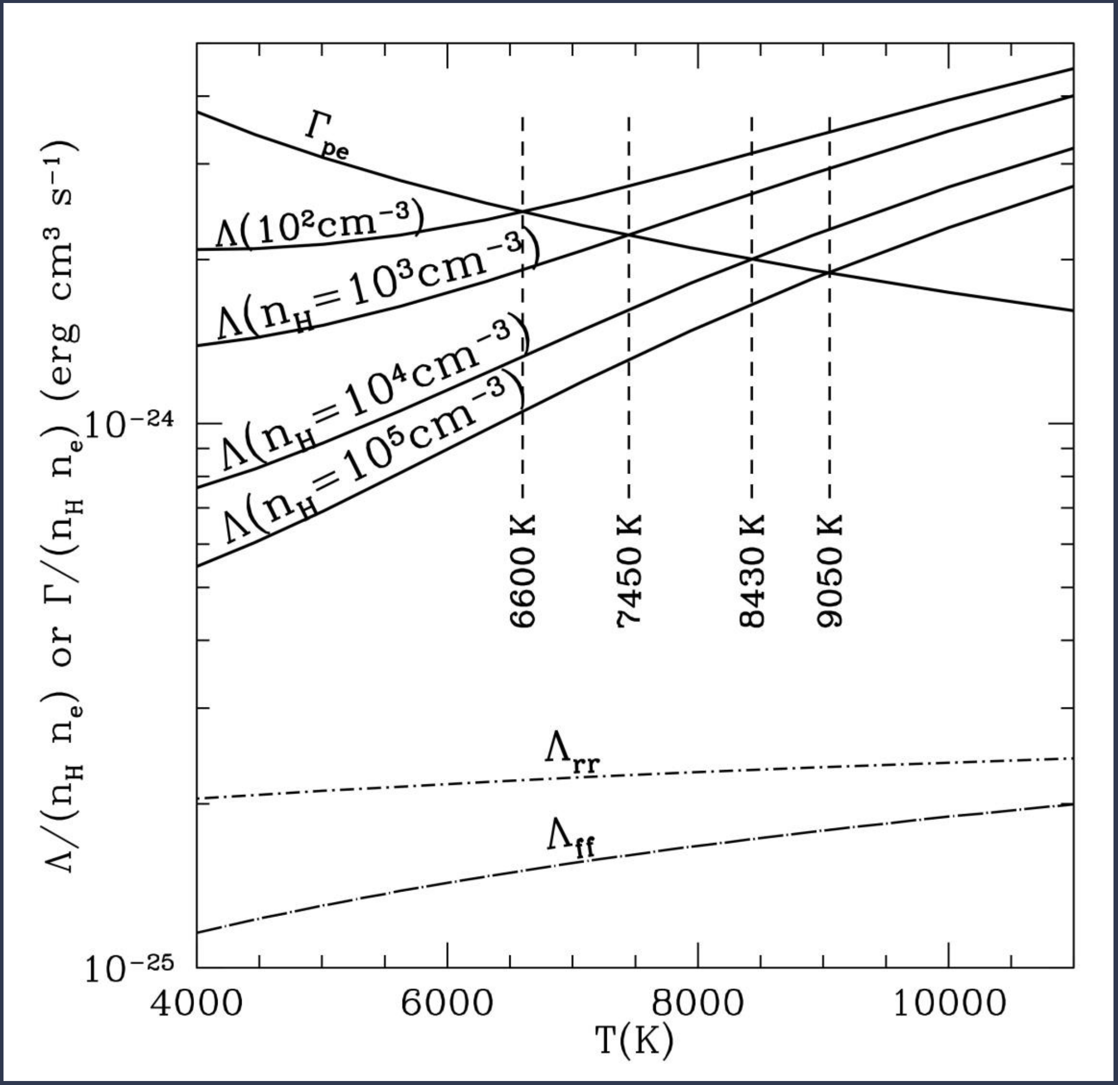
(Draine, Fig. 27.2)



low metal abundance

high metal abundance

Effect of density



Why does the temperature increase with density?

(Draine, Fig. 27.3)

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Thermal balance in the WNM/CNM

Heating:

- cosmic rays
- photoelectric effect on dust grains (photons with $E < 13.6$ eV)

Cooling:

- collisionally excited lines (mainly [CII] 158 μm & [OI] 63 μm)

(dominant mechanisms in red)

Heating by the photoelectric effect

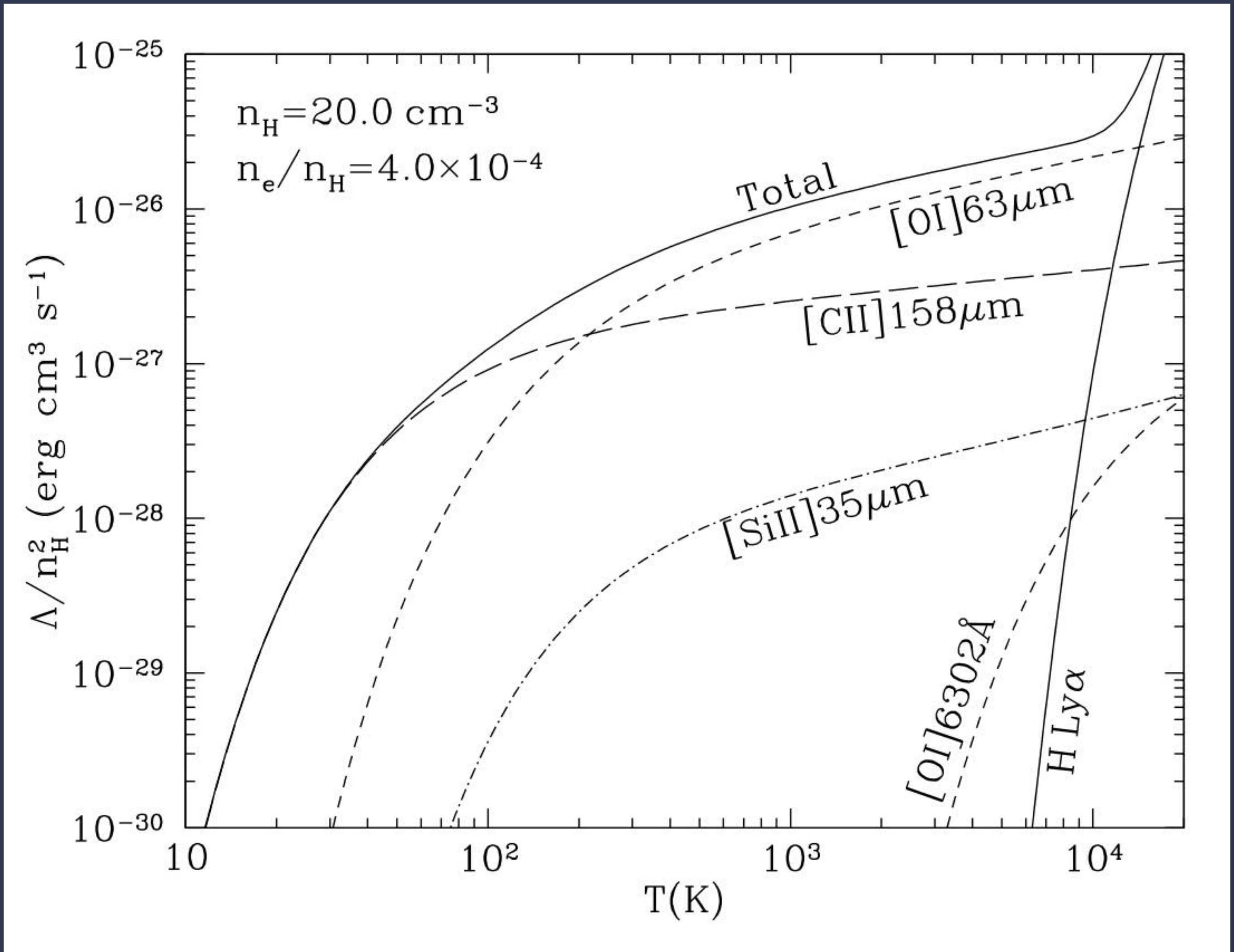
Need to overcome a work function of 4.5 eV, so need UV photons. In practice, most effective range 8-13.6 eV.

Calculation shows that only 0.1 – 0.5% of incident UV radiation goes into photoelectric heating (where does the rest go?).

So this is a very inefficient heating mechanism.

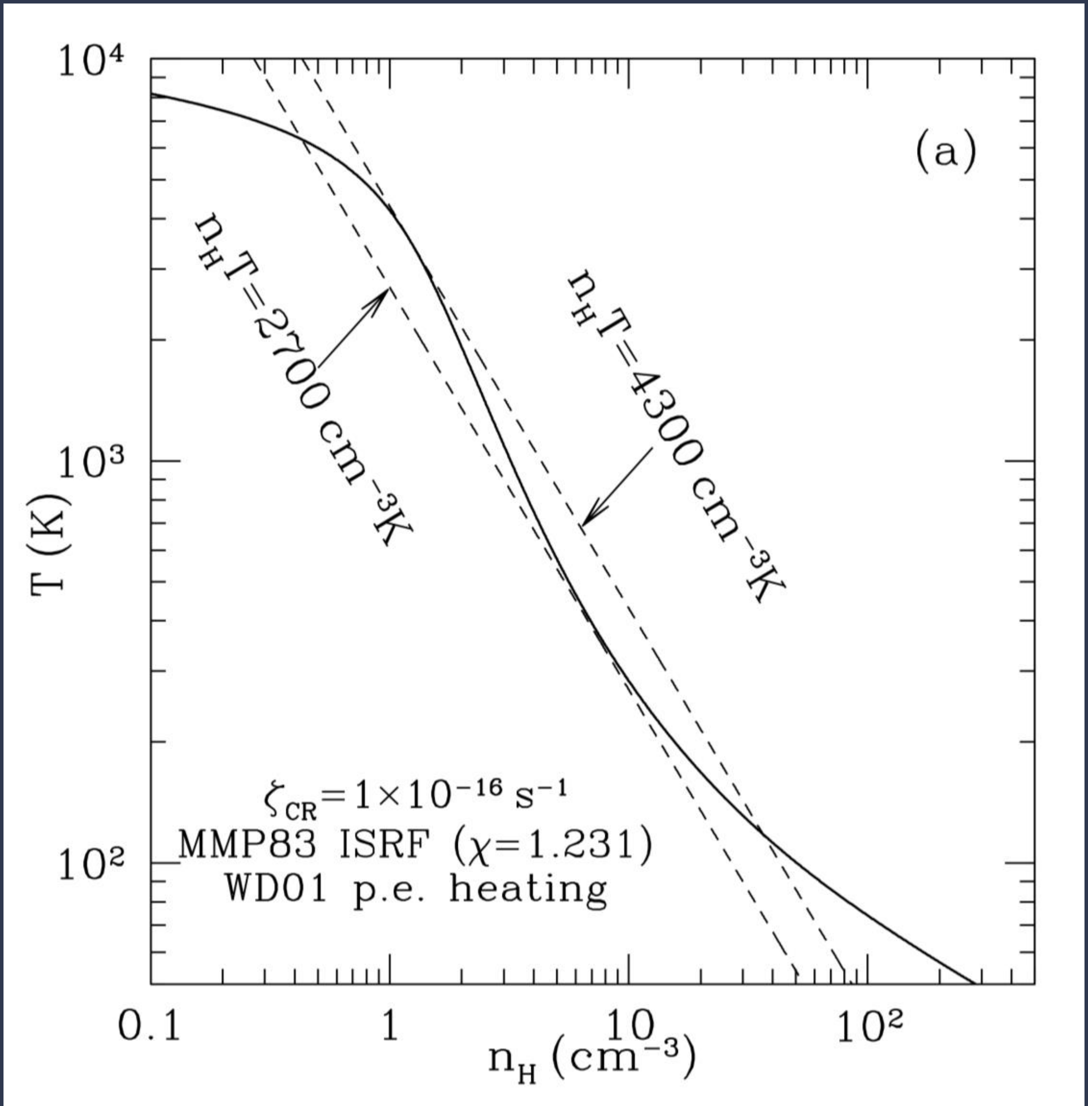
Nevertheless, this is more effective than cosmic ray heating (in the standard ISRF, and with Galactic cosmic ray fluxes).

Cooling the atomic medium



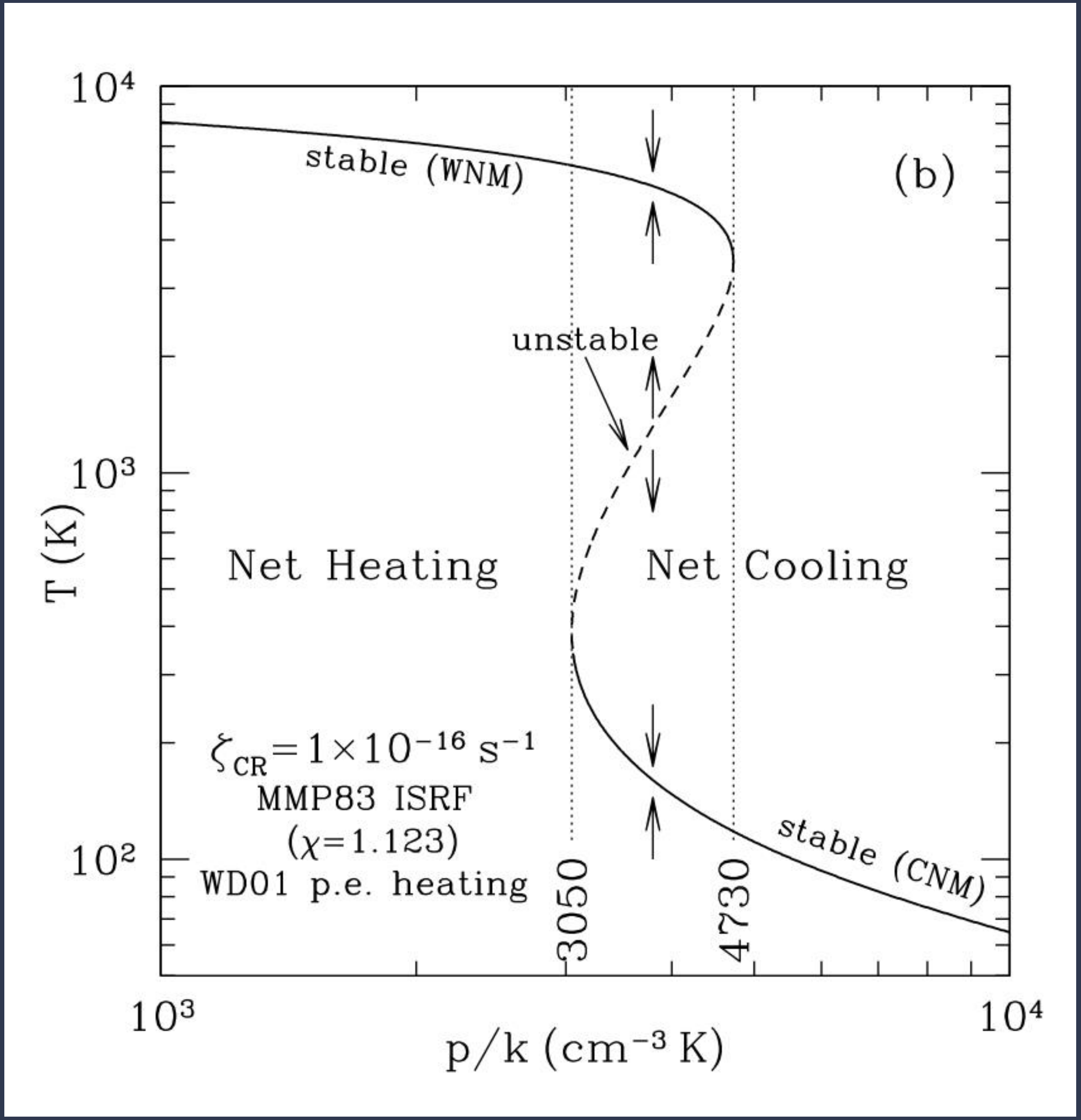
(Draine, Fig. 30.1b)

Equilibrium temperature in the atomic medium



(Draine, Fig. 30.2a)

Two-phase atomic medium



(Draine, Fig. 30.2b)

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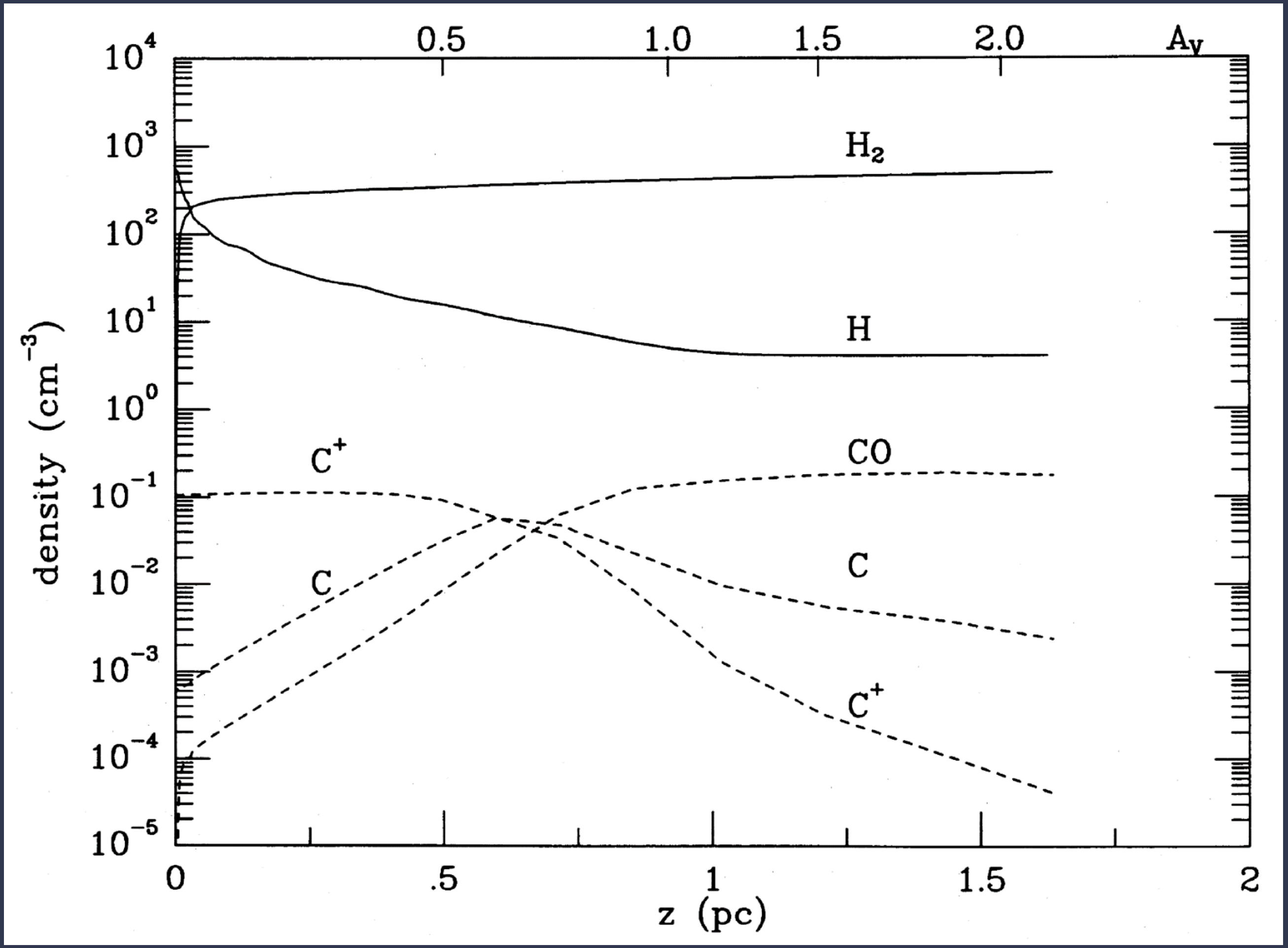
Structure of a molecular cloud



n_H = 500 cm^{-3}
I_{UV} = 1

cloud
edge

cloud envelope and cloud core have different thermal properties

Thermal balance in molecular cloud envelope

The cloud envelope is effectively a PDR, and forms the transition from the CNM to the molecular cloud core.

Heating in the cloud envelope:

- photoelectric effect on dust grains (photons with E < 13.6 eV)

Cooling in the cloud envelope:

- collisionally excited lines (mainly [CII] 158 μm & [OI] 63 μm)

So this is very similar to the CNM (with similar resulting temperatures)

Thermal balance in molecular cloud core

UV photons are absorbed by dust and do not penetrate into the cloud core. Therefore:

Heating in the cloud core:

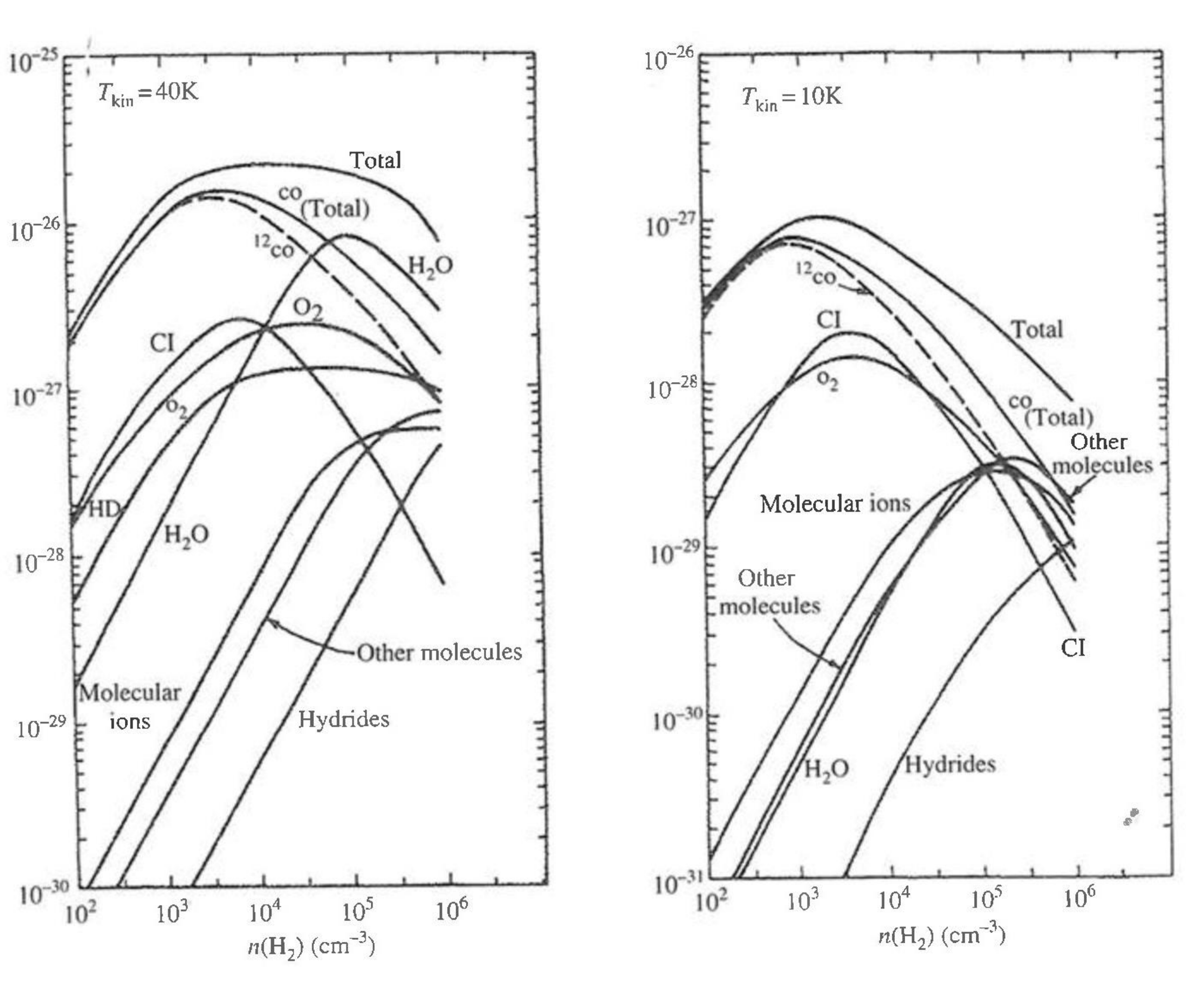
- cosmic ray heating

Cooling in the cloud core:

- collisionally excited molecular lines

Resulting temperatures are low: ~ 15 - 30 K

Cooling of molecular gas



cooling per H_2 molecule

(Tielens, 2005)

Forming the first star

The first star must have formed in an environment with only H and He (and trace elements D and Li).

Steps needed:

1. cooling the neutral gas (difficult since no metals)
2. forming H_2 molecules (difficult since no dust grains)
3. cooling further (difficult since no metals)

Primordial (metal-free) star formation was totally diffenent from star formation today.

Next lecture

Interstellar dust

- Extinction
- Dust models
- PAHs, silicates, ices
- Dust formation and destruction
- Dust temperature
- Infrared emission
- Infrared galaxies