Interstellar Medium 2020

Lecture 4: Ionization and Recombination

Sterrewacht Leiden

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Course Contents

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2. Physical conditions and radiative processes
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Today’s Lecture

1. Photoionization & recombination
2. Recombination lines

Ionization processes

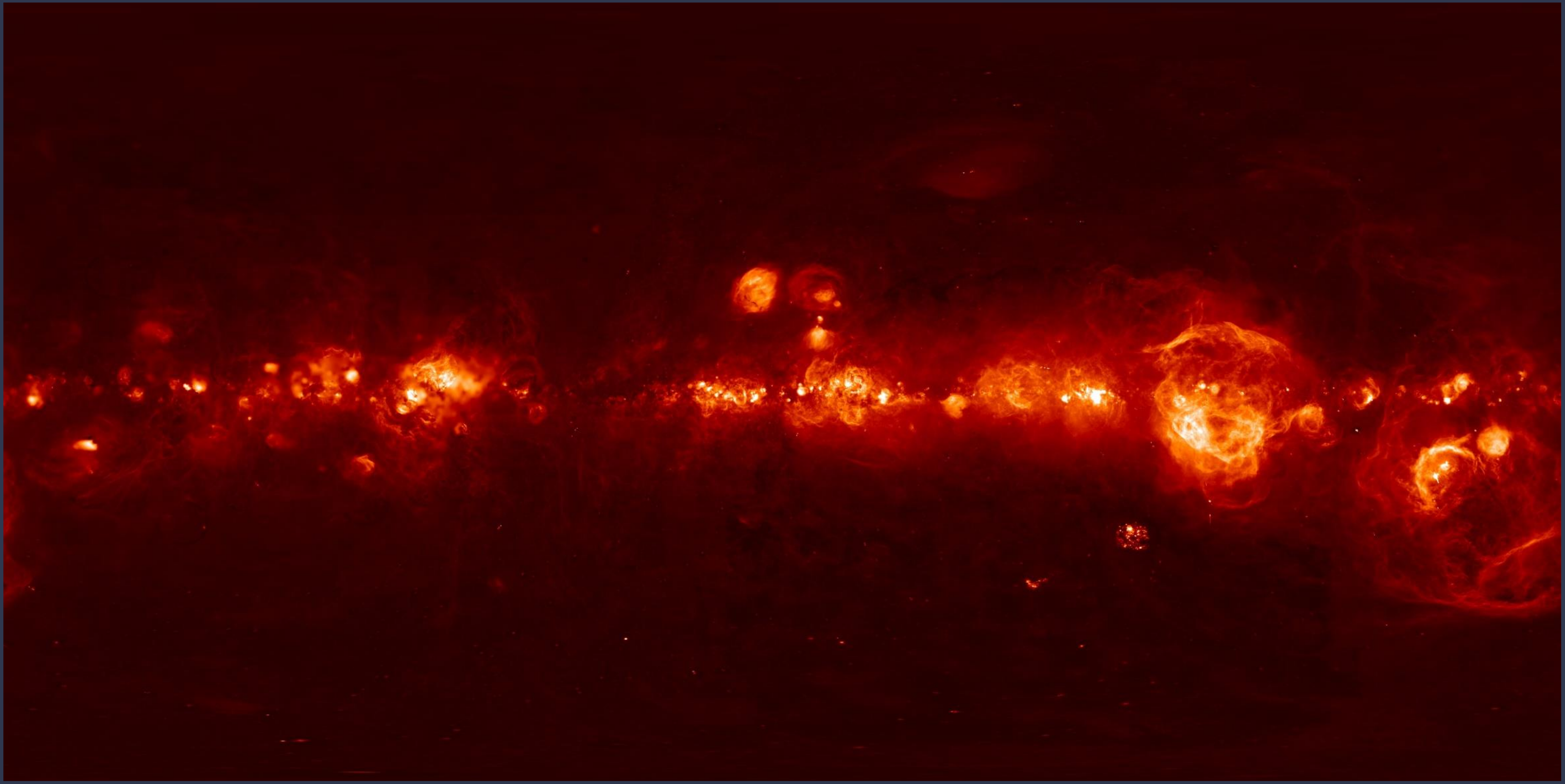
1. Photoionization (WIM & HII regions)

2. Collisional ionization (SNRs – not covered in this course)

3. Cosmic ray ionization (molecular cloud interiors – important for astrochemistry)

In this lecture: photoionization

The Warm Ionized Medium and HII Regions



composite Hα map compiled by Finkbeiner from WHAM, VTSS & SHASSA

Evolved HII Region: The Rosette Nebula

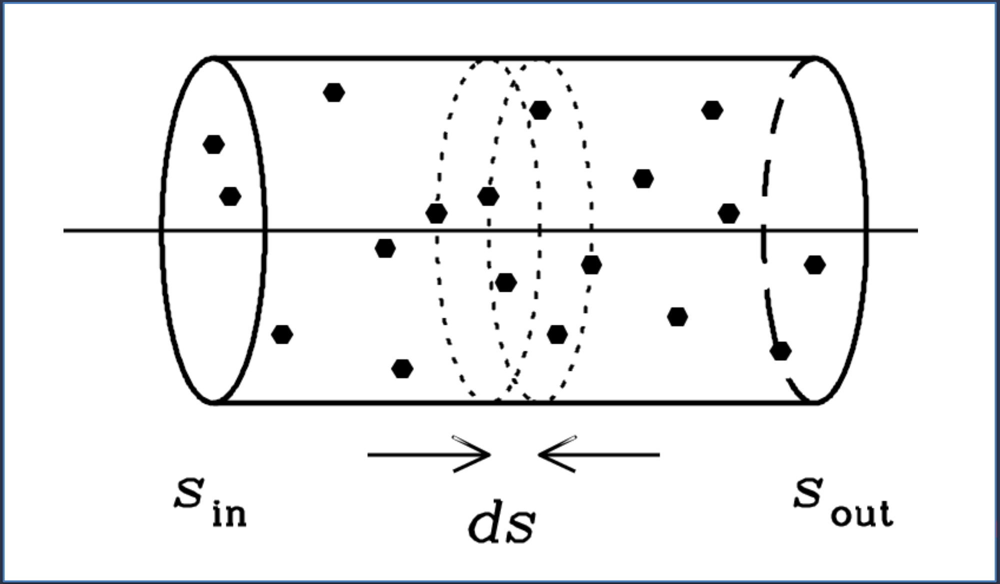
Ionization-recombination balance

photoionization rate = recombination rate

- photoionization rate = # photoionizations per unit of volume and unit of time

- recombination rate = # recombinations per unit of volume and unit of time

Photoionization



X + $h\nu$ → X$^+$ + e^-

cylinder length: $c\,dt$

photoionization cross section: $\sigma_{\text{pi}}(\nu)$ ("photoelectric photoionization")

photoionization rate $$\zeta_{\text{pi}} = \int_{\nu_0}^{\infty} n_X \frac{u_\nu}{h\nu} \sigma_{\text{pi}}(\nu) c\, d\nu$$ [cm^{-3} s^{-1}]

NB: really should consider photoionization from every state separately but in practice almost every particle is in ground state

Photoionization cross sections

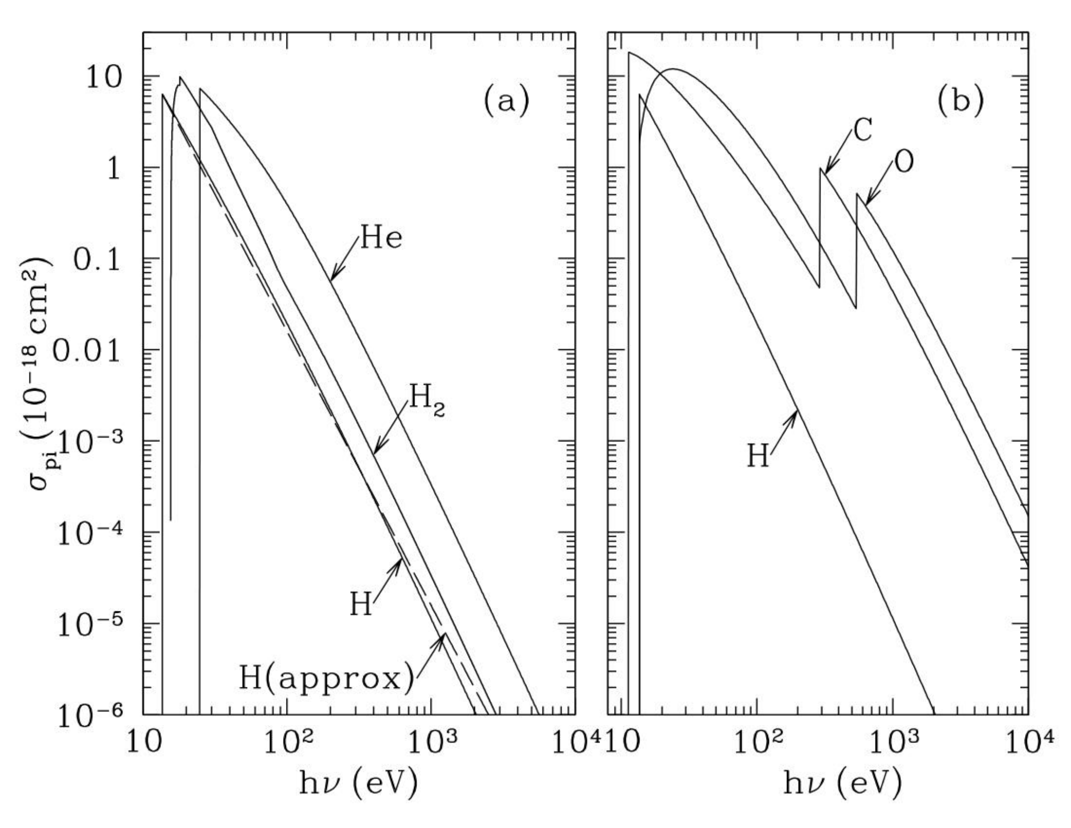


figure from Draine

For hydrogenic atoms (1 electron): to good approximation

$$\sigma_{\mathrm{pi}} = \sigma_0 \left(\frac{h\nu}{Z^2 I_{\mathrm{H}}} \right)^{-3}$$

for $h\nu > Z^2 I_H$

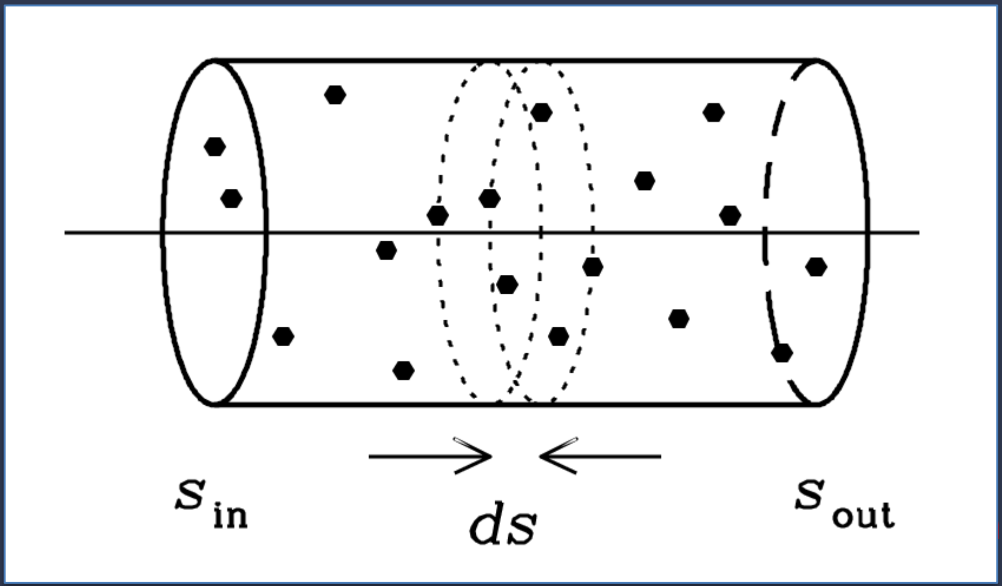
Z = nuclear charge

I_H = hydrogen ionization potential = 13.6 eV (λ_0 = 912 Å)

σ_0 = photoionization cross section at the ionization edge = $6.3 \cdot 10^{-18} Z^2$ cm^2

NB: for multi-electron atoms more complex (inner shell absorption etc)

Recombination



$X^+ + e^- \rightarrow X + h\nu$

with the election captured in any state *nl* that was previously unoccupied (Pauli principle)

("radiative recombination")

Now consider all states *nl* separately

Maxwell distribution

Recombination rate into *nl*

$$\zeta_{nl} = n_e n_{X^+} \int_0^\infty \sigma_{nl}(v)\, v\, f_v(T_k)\, dv = \alpha_{nl}(T_k) n_e n_{X^+}$$

[cm^{-3} s^{-1}]

With $\alpha_{tot}(T_k) = \sum_{nl} \alpha_{nl}(T_k)$ we can write $\zeta_{rr} = \alpha_{tot}(T_k) n_e n_{X^+}$

$\alpha_{tot}(T_k)$ [cm^3 s^{-1}] is the total recombination coefficient.

Photoionization equilibrium

$\zeta_{pi} = \zeta_{rr}$ so

$$\int_{\nu_0}^{\infty} n_X \frac{u_\nu}{h\nu} \sigma_{\mathrm{pi}}(\nu) c \, d\nu = \alpha_{\mathrm{tot}}(T_k) n_e n_{\mathrm{X}^+}$$

- must be solved numerically
- note ionization goes as $(\text{density})^1$ but recombination as $(\text{density})^2$ so high density favours recombination (and therefore higher neutral fraction)

Today's Lecture

1. Photoionization & recombination
2. Recombination lines

Recombination lines

recombination into any level *nl*

→ radiative decay

→ photon emission spectrum: recombination lines

Important: recombination line flux is proportional to recombination rate (see later)

- Hydrogen recombination lines are a key probe of ionization, star formation, etc.
- Recombination lines can also be detected for helium (and in some cases carbon)

Hydrogen quantum numbers and energy levels

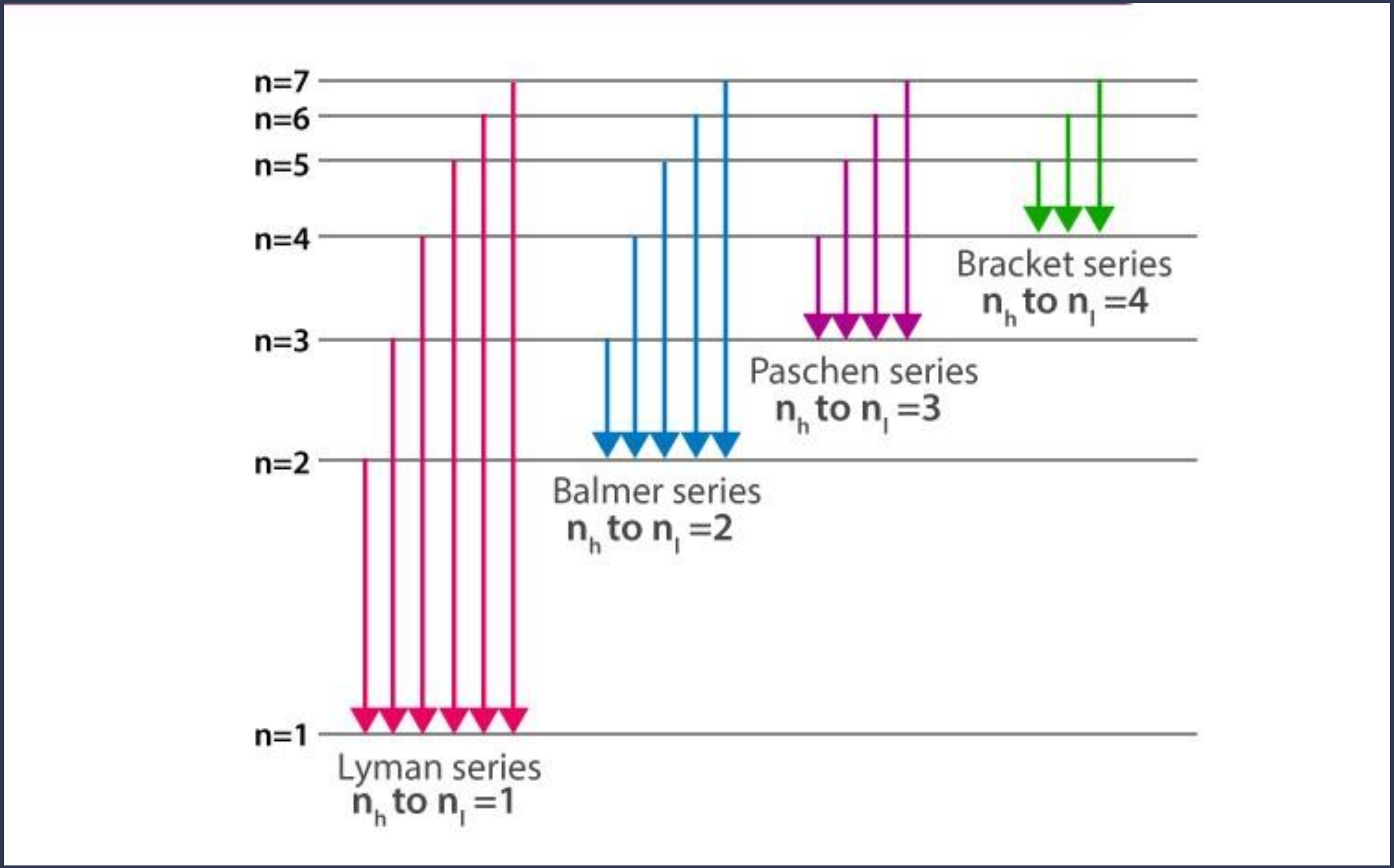
- Discrete energy levels, characterized by three quantum numbers *n*, *l*, *m*
  $n = 1, 2, 3, 4, \ldots$ principal quantum number
  $l = 0, 1, 2, \ldots n\text{-}1$ angular momentum quantum number
  $m = -l, -l+1, \ldots l\text{-}1, l$ magnetic quantum number

- Level energies independent of *l* and *m*:

$$\boxed{E_n = -hcR_{\mathrm{H}}\frac{1}{n^2}}$$

with $R_H = 109677.585\ \mathrm{cm}^{-1}$: Rydberg constant for H

Hydrogen spectrum



Some important hydrogen lines

Lyα:	λ_{vac}= 1215.68 Å	(space UV)		
Hα:	λ_{air}= 6562.73 Å	(red)	3-2	Balmer lines
Hβ:	λ_{air}= 4861.33 Å	(blue)	4-2	
Hγ:	λ_{air}= 4340.47 Å	(blue)	5-2	
Hδ:	λ_{air}= 4101.47 Å	(violet)	6-2	
Paα:	λ_{air}= 1.875 μm	(poor transmission)		
Brα:	λ_{air}= 4.051 μm	(difficult)		
Brγ:	λ_{air}= 2.166 μm	(in infrared K band)		

Hydrogen: Case A and Case B recombination

- Case A: all recombination lines optically thin

$$\alpha_{\mathrm{A}}(T_k) = \sum_{n=1}^{\infty} \sum_{l=0}^{n-1} \alpha_{nl}(T_k)$$

- Case B: all Lyman lines are optically thick, all other recombination lines are optically thin

$$\alpha_{\mathrm{B}}(T_k) = \sum_{n=2}^{\infty} \sum_{l=0}^{n-1} \alpha_{nl}(T_k) = \alpha_{\mathrm{A}}(T_k) - \alpha_{1s}(T_k)$$

ground state

since every Lyman line (and continuum) photon (which connect to the ground state) is reabsorbed.

The “on-the-spot” approximation

Under Case B conditions, photons emitted in the Lyman lines (or the Lyman continuum) during the recombination process and subsequent decay are reabsorbed.

“On-the-spot” approximation: this reabsorption happens at the place where the photons were emitted.

→ net effect: as if those photons were not there in the first place

Broadly speaking:

- ISM conditions are always Case B
- IGM conditions can be Case A

Hydrogen recombination line spectrum (1)

For hydrogen $A_{n+1,n} \approx \frac{5.3 \cdot 10^9}{n^5} s^{-1}$ so for $n \approx 100$, $t_{\mathrm{rad}} \approx 1$ s.

This is also approximately the time between collisions.

→ for $n << 100$, spontaneous transitions dominate and collisions can be ignored.

So recombination line spectrum (line ratios) can "simply" be calculated from:

1. Einstein *A* coefficients
2. Case A or B (in Case B, all Einstein *A*'s for the Lyman lines are set to 0).
3. $\alpha_{nl}(T_k)$: slow function of T_k which is always ~ 8000 K for WIM

Hydrogen recombination line spectrum (2)

Recombination rate $$\zeta_{rr} = \alpha_{\mathrm{B}}(T_k) n_e n_p$$

Now let $\alpha_{nl\rightarrow n'l'}(T_k)$ / $\alpha_{\mathrm{B}}(T_k)$ be the fraction of recombinations that produce a photon in the *nl* → *n'l'* transition.

Then the photon production rate in the *nl*→*n'l'* line is

$$\alpha_{nl\rightarrow n'l'}(T_k) n_e n_p$$

and the emissivity in this line then is $$j_\nu = \frac{h\nu_{ul}}{4\pi} \alpha_{nl\rightarrow n'l'}(T_k) n_e n_p \varphi_\nu$$

See Draine, Table 14.2, where $\alpha_{nl\rightarrow n'l'}(T_k)$ is written, e.g., for Hα, as $\alpha_{\mathrm{eff,\,H\alpha}}$

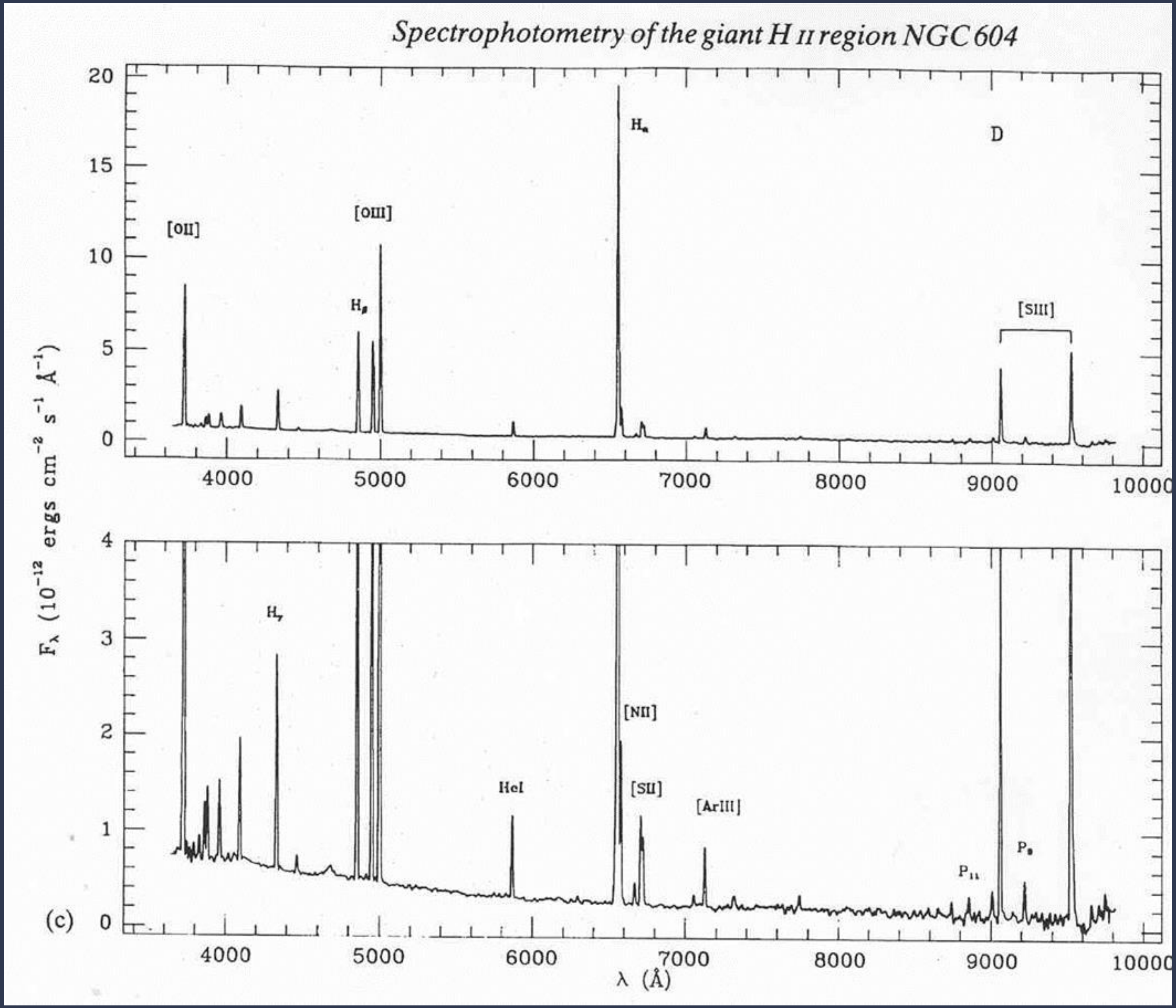
Hydrogen recombination line spectrum

Table 14.2 Case B Hydrogen Recombination Spectrum[a] for $n_e = 10^3\ \mathrm{cm}^{-3}$

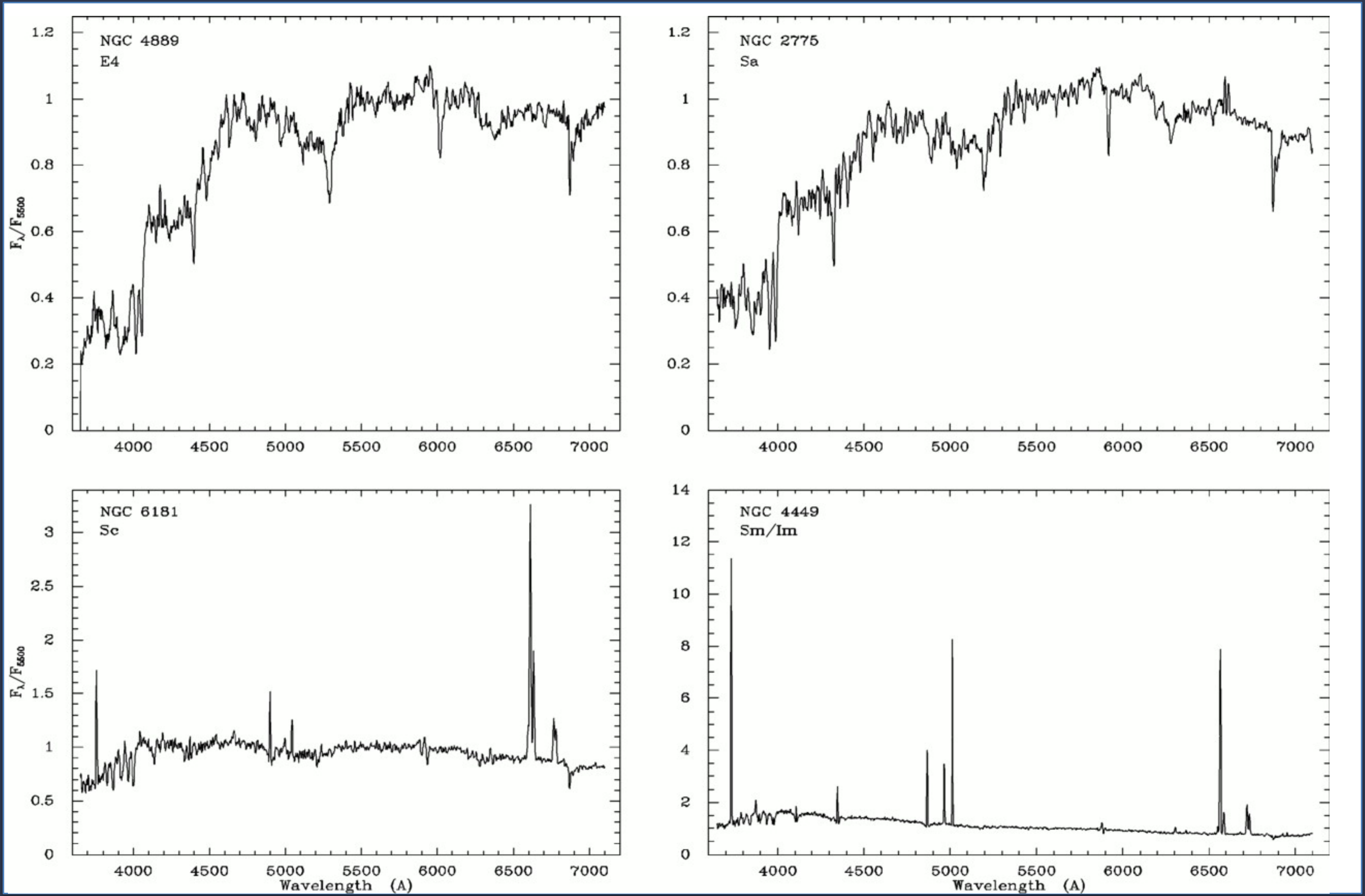
	T(K) 5000	10,000	20,000
$\alpha_B(\mathrm{cm}^3\,\mathrm{s}^{-1})$	4.53×10^{-13}	2.59×10^{-13}	1.43×10^{-13}
$\alpha_{\mathrm{eff},2s}/\alpha_B$	0.305	0.325	0.356
$\alpha_{\mathrm{eff,H}\alpha}(\mathrm{cm}^3\,\mathrm{s}^{-1})$	2.20×10^{-13}	1.17×10^{-13}	5.96×10^{-14}
$\alpha_{\mathrm{eff,H}\beta}(\mathrm{cm}^3\,\mathrm{s}^{-1})$	5.40×10^{-14}	3.03×10^{-14}	1.61×10^{-14}
$4\pi j_{\mathrm{H}\beta}/n_e n_p(\mathrm{erg\,cm}^3\,\mathrm{s}^{-1})$	2.21×10^{-25}	1.24×10^{-25}	6.58×10^{-26}
Balmer-line intensities relative to Hβ 0.48627 μm			
$j_{\mathrm{H}\alpha\,0.65646}/j_{\mathrm{H}\beta}$	3.03	2.86	2.74
$j_{\mathrm{H}\beta\,0.48627}/j_{\mathrm{H}\beta}$	1.	1.	1.
$j_{\mathrm{H}\gamma\,0.43418}/j_{\mathrm{H}\beta}$	0.459	0.469	0.475
$j_{\mathrm{H}\delta\,0.41030}/j_{\mathrm{H}\beta}$	0.252	0.259	0.264
$j_{\mathrm{H}\epsilon\,0.39713}/j_{\mathrm{H}\beta}$	0.154	0.159	0.163
$j_{\mathrm{H8}\,0.38902}/j_{\mathrm{H}\beta}$	0.102	0.105	0.106
$j_{\mathrm{H9}\,0.38365}/j_{\mathrm{H}\beta}$	0.0711	0.0732	0.0746
$j_{\mathrm{H10}\,0.37990}/j_{\mathrm{H}\beta}$	0.0517	0.0531	0.0540
Paschen ($n \to 3$) line intensities relative to corresponding Balmer lines			
$j_{\mathrm{P}\alpha\,1.8756}/j_{\mathrm{H}\beta}$	0.405	0.336	0.283
$j_{\mathrm{P}\beta\,1.2821}/j_{\mathrm{H}\gamma\,0.43418}$	0.399	0.347	0.305
$j_{\mathrm{P}\gamma\,1.0941}/j_{\mathrm{H}\delta\,0.41030}$	0.391	0.348	0.311
$j_{\mathrm{P}\delta\,1.0052}/j_{\mathrm{H}\epsilon\,0.39713}$	0.386	0.348	0.314
$j_{\mathrm{P}\epsilon\,0.95487}/j_{\mathrm{H8}\,0.38902}$	0.382	0.348	0.316
$j_{\mathrm{P9}\,0.92317}/j_{\mathrm{H9}\,0.38365}$	0.380	0.347	0.317
$j_{\mathrm{P10}\,0.90175}/j_{\mathrm{H10}\,0.37990}$	0.380	0.347	0.317
Brackett ($n \to 4$) line intensities relative to corresponding Balmer lines			
$j_{\mathrm{Br}\alpha\,4.0523}/j_{\mathrm{H}\gamma\,0.43418}$	0.223	0.169	0.131
$j_{\mathrm{Br}\beta\,2.6259}/j_{\mathrm{H}\delta\,0.41030}$	0.219	0.174	0.141
$j_{\mathrm{Br}\gamma\,2.1661}/j_{\mathrm{H}\epsilon\,0.39713}$	0.212	0.174	0.144
$j_{\mathrm{Br}\delta\,1.9451}/j_{\mathrm{H8}\,0.38902}$	0.208	0.173	0.145
$j_{\mathrm{Br}\epsilon\,1.8179}/j_{\mathrm{H9}\,0.38365}$	0.204	0.173	0.146
$j_{\mathrm{Br10}\,1.7367}/j_{\mathrm{H10}\,0.37990}$	0.202	0.172	0.146

table from Draine

HII Region spectra



Galaxy spectra



For discussion

- Assume we can image Hα and Hβ emission from an HII region. How can we correct for extinction?

- Does it matter whether the dust is located in a foreground absorbing cloud or is mixed with the ionized gas?

Recombination lines: key points (so far)

- Recombination lines result from the downward cascade following recombination in ionized gas
- Recombination to the ground-state leads to ionizing photons; these immediately lead to ionization ("on-the-spot" approximation)
- In Galactic conditions, case B recombination is valid: Lyman lines (lines connecting to the ground state) optically thick, all other lines optically thin
- Recombination spectrum (line ratios) for $n \ll 100$ is independent of density (spontaneous decay more rapid than collisions); temperature comes in through T-dependence of recombination coefficient α; but T of HII regions fairly uniform 5000-10000 K; so only weak T-dependence
- High n (radio) recombination lines are much more complicated: density dependence and stimulated emission

Next lecture

HII Regions

1. Strömgren spheres
2. Radio emission from HII regions
3. Calculating Star Formation Rates
4. Structure of HII regions
5. HII regions containing heavy elements
6. Dusty HII regions
7. Ultracompact HII regions
8. HII region evolution