Interstellar Medium 2020

Lecture 5: HII Regions

Sterrewacht Leiden

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2. Physical conditions and radiative processes
3. The atomic interstellar medium
4. Ionization and recombination
5. HII regions
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11. Shocks, supernova remnants and the 3-phase ISM
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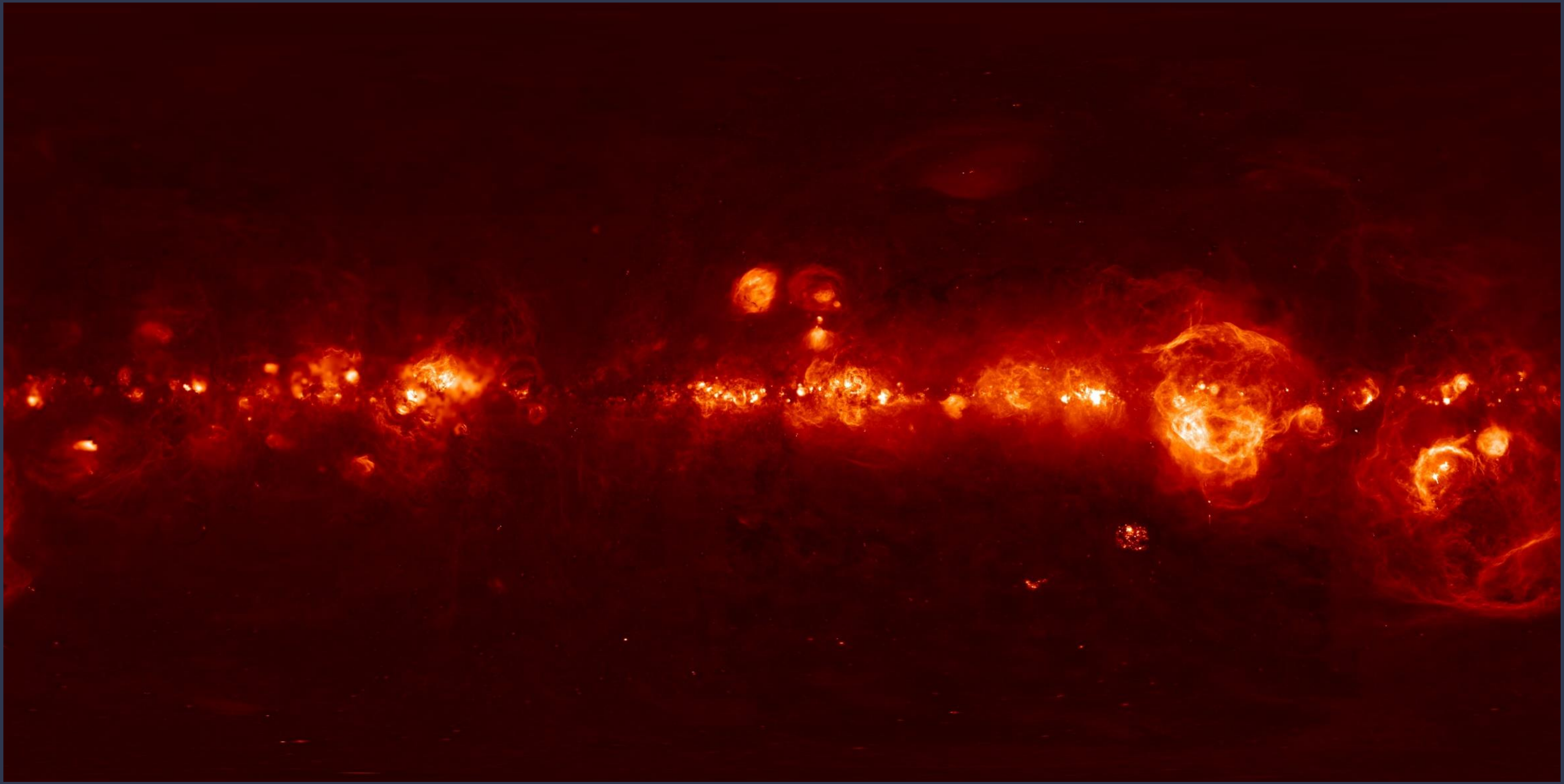
The Warm Ionized Medium and HII Regions



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

Evolved HII Region: The Rosette Nebula

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

Today’s lecture

HII Regions

1. The Strömgren sphere
2. Recombination lines and radio continuum emission
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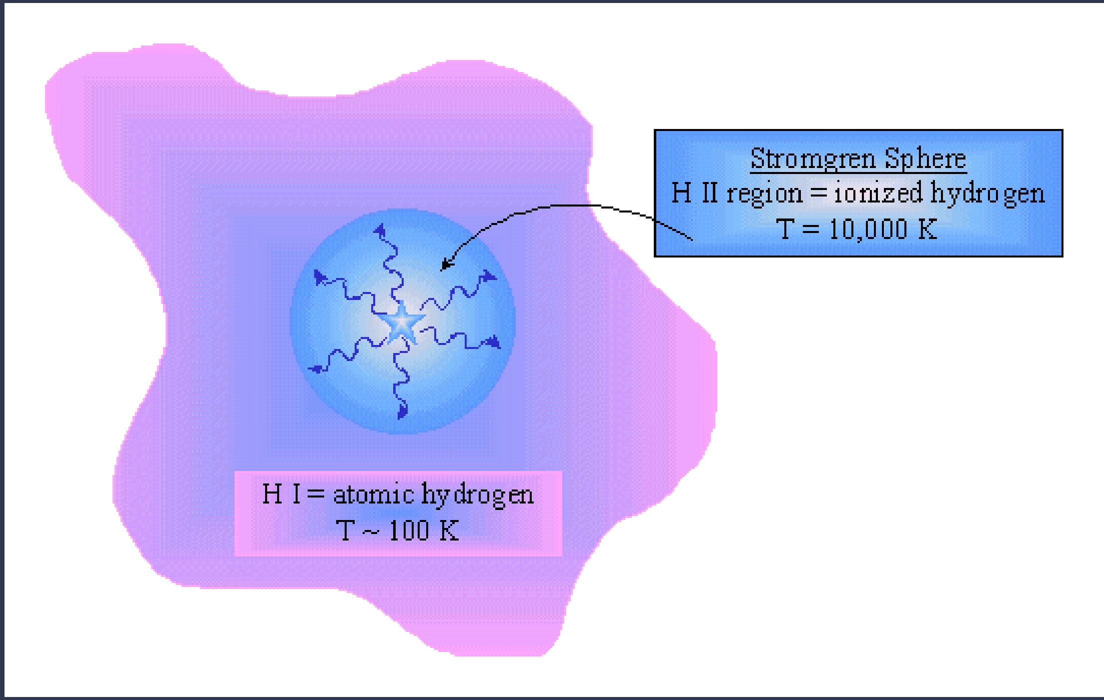
4. HII regions containing heavy elements
5. Real HII regions

Strömgren spheres



Strömgren radius of an HII region: radius R_s where all stellar Lyman continuum (λ < 912 Å) photons have been absorbed (Strömgren 1930). So fully ionized for $r < R_s$, fully neutral for $r > R_s$.

Simple assumptions:
pure hydrogen nebula, with constant density of hydrogen n_H.
So for $r < R_s$: $n_e = n_p = n_H$

Strömgren radius

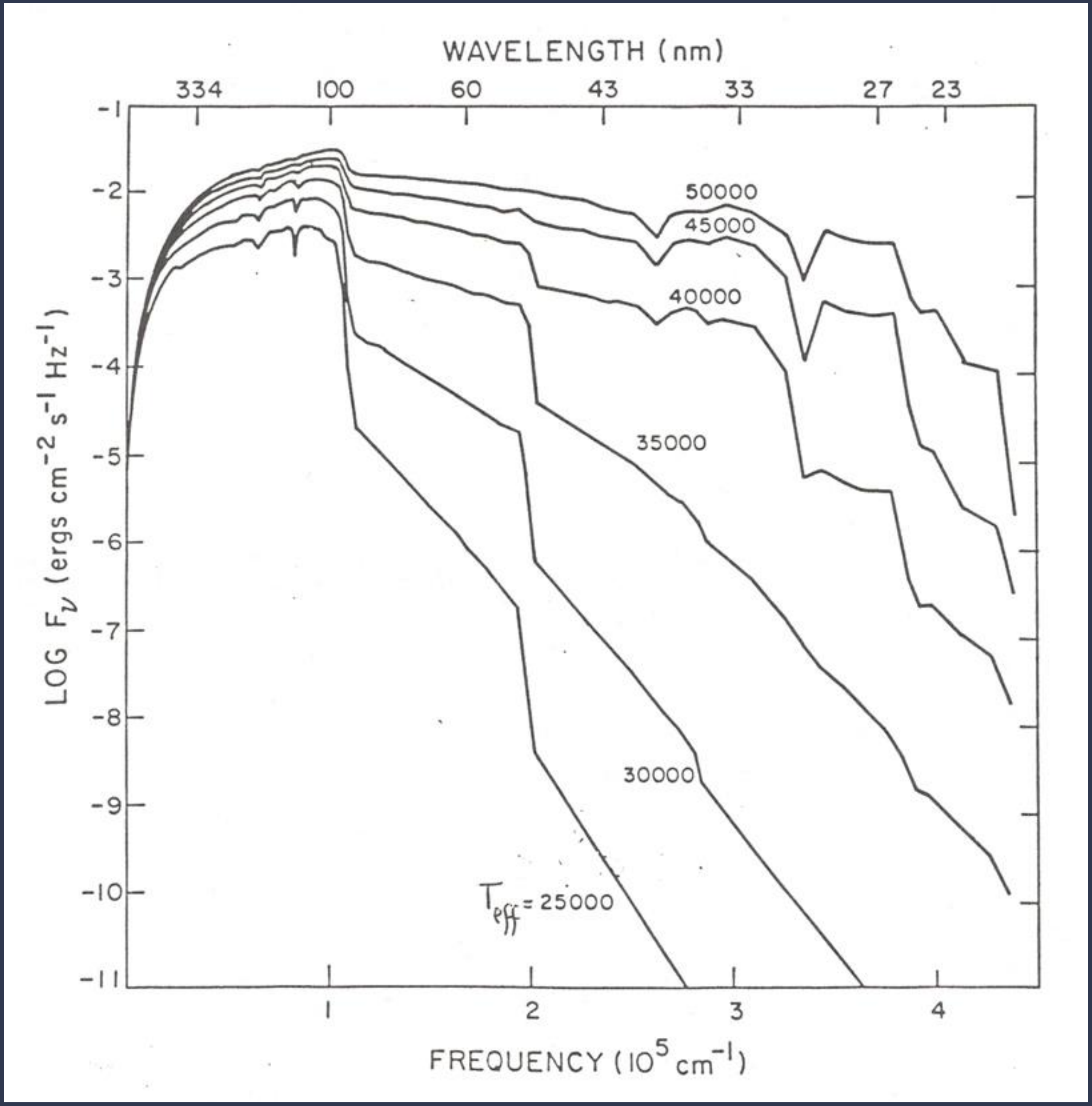
total number of ionizations = total number of recombinations

Ionizations: $Q_0 = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$ Lyman continuum photon production rate by central star or star cluster

Recombinations: $\frac{4}{3}\pi R_s^3 \alpha_\mathrm{B} n_e n_p = \frac{4}{3}\pi R_s^3 \alpha_\mathrm{B} n_\mathrm{H}^2$ case B, note $\alpha_\mathrm{B}(T)$

So: $\boxed{R_s = \left(\frac{3Q_0}{4\pi\alpha_\mathrm{B} n_\mathrm{H}^2}\right)^{\frac{1}{3}} = 3.2\ \mathrm{pc} \left(\frac{Q_0}{10^{49}\ \mathrm{s}^{-1}}\right)^{\frac{1}{3}} \left(\frac{n_\mathrm{H}}{100\ \mathrm{cm}^{-3}}\right)^{-\frac{2}{3}}}$ (at $T = 10^4$ K)

Spectra of O stars

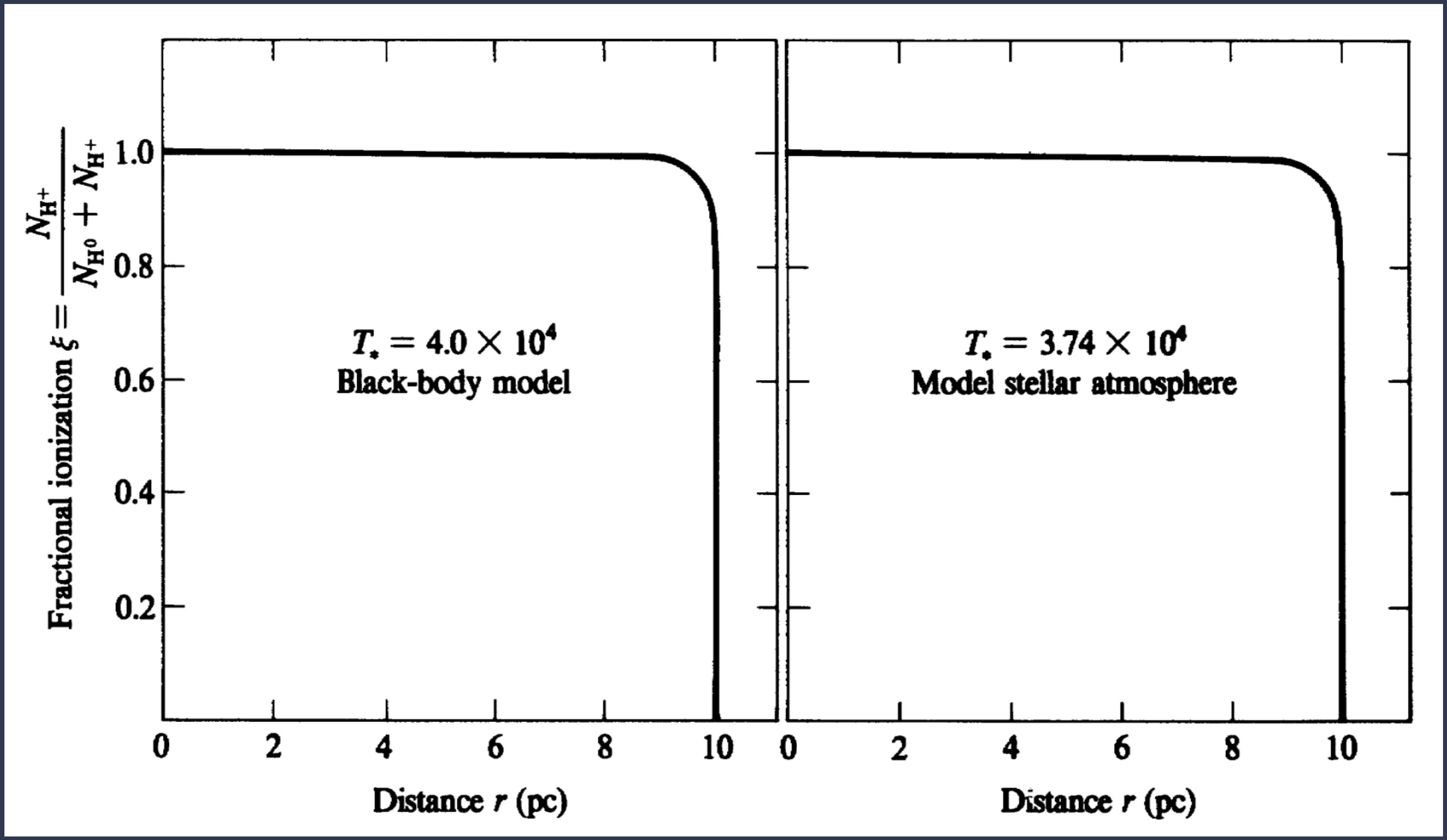


Calculated properties of Strömgren spheres

Spectral type	M_v	$T_*(^\circ K)$	Log $Q(H^0)$ (photons/sec)	Log $N_e N_p r_1^3$ (N in cm^{-3}; r_1 in pc)	r_1 (pc) ($N_e = N_p$ = 1 cm^{-3})
O5	– 5.6	48,000	49.67	6.07	108
O6	– 5.5	40,000	49.23	5.63	74
O7	– 5.4	35,000	48.84	5.24	56
O8	– 5.2	33,500	48.60	5.00	51
O9	– 4.8	32,000	48.24	4.64	34
O9.5	– 4.6	31,000	47.95	4.35	29
B0	– 4.4	30,000	47.67	4.07	23
B0.5	– 4.2	26,200	46.83	3.23	12

NOTE: $T = 7500^\circ$ K assumed for calculating α_B.

Ionization structure of a pure hydrogen HII region



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Recombination line intensity

Assume: optically thin line (so not for Lyman lines)
case B recombination
no stimulated emission (so not valid in radio regime)

Recombination line emissivity $$j_\nu = \frac{h\nu}{4\pi} n_e n_p \alpha_{nl\to n'l'}(T_k)\varphi_\nu$$

Equation of transfer (for simplicity assume no background source):

$$I_\nu = \frac{j_\nu}{\kappa_\nu}(1 - e^{-\tau_\nu}) \approx \frac{j_\nu}{\kappa_\nu}\tau_\nu = \int \frac{j_\nu}{\kappa_\nu}\kappa_\nu ds = \int j_\nu ds$$

so $$\int I_\nu d\nu = \frac{h\nu}{4\pi}\alpha_{nl\to n'l'}(T_k)\int n_e n_p\, ds = \frac{h\nu}{4\pi}\alpha_{nl\to n'l'}(T_k)\ \mathrm{EM}$$

where EM [cm^{-6} pc] is the Emission Measure: $$\mathrm{EM} = \int n_e n_p\, ds$$

Radio emission from an HII region

Thermal radio continuum emission (Bremsstrahlung) arises because from charges accelerating eachother → photon emission

The optical depth for this emission is again proportional to EM:

$$\tau_\nu = 0.33 \left(\frac{10^4\mathrm{K}}{T_e}\right)^{1.35} \left(\frac{1\ \mathrm{GHz}}{\nu}\right)^{2.1} \frac{\mathrm{EM}}{10^6\mathrm{cm}^{-6}\mathrm{pc}}$$

where the electron temperature T_e is the kinetic temperature of the electrons.

Note optically thick at low *v*, thin at high *v.*

Optically thin radio emission

If optically thin (for simplicity assume no background source):

$$T_b(\nu) = T_e(1 - e^{-\tau_\nu}) \approx \tau_\nu T_e = 0.33 \left(\frac{10^4\mathrm{K}}{T_e}\right)^{0.35} \left(\frac{1\ \mathrm{GHz}}{\nu}\right)^{2.1} \frac{\mathrm{EM}}{10^6\mathrm{cm}^{-6}\mathrm{pc}}$$

Since this is only a weak function of T_e (which has only a small range for HII regions), we can use this to determine EM (free from extinction).

Combining this with recombination lines in the optical/IR, which also measure EM, this gives a measurement of the extinction.

Emission Measure

$$\mathrm{EM} = \int n_e n_p \, ds$$

Recombination line intensity (and radio continuum intensity) are proportional to EM, not column density!

Therefore, ionized gas mass hard to determine.

Simple solution would be: somehow determine density and assume HII region has constant density.

In practice this fails: there are large density variations, and the EM is dominated by the highest densities.

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What does EM measure?

Take an HII region, and determine its total flux in the recombination line *nl→n'l'* :

$$\int I_\nu d\nu = \frac{h\nu}{4\pi} \alpha_{nl\to n'l'}(T)\ \mathrm{EM}$$

so

$$\int F_\nu d\nu = \int\int I_\nu d\nu\ d\Omega = \frac{h\nu}{4\pi D^2} \alpha_{nl\to n'l'}(T) \int \mathrm{EM}\ dA$$

and the line luminosity is

$$\int L_\nu d\nu = 4\pi D^2 \int F_\nu d\nu = h\nu \alpha_{nl\to n'l'}(T) \int \mathrm{EM}\ dA$$

Simplify by taking constant density, spherical HII region:

$$\int \mathrm{EM}\ dA = \int n_e^2\ dV = \frac{4\pi}{3} R_s^3 n_e^2 = \frac{Q_0}{\alpha_\mathrm{B}(T)}$$

so

$$L_{nl\to n'l'} = \int L_\nu d\nu = h\nu \frac{\alpha_{nl\to n'l'}(T)}{\alpha_\mathrm{B}(T)} Q_0$$

(can easily be shown also for non-homogeneous HII regions)

What recombination lines measure

$$L_{nl\to n'l'} = h\nu \, \frac{\alpha_{nl\to n'l'}(T)}{\alpha_{\mathrm{B}}(T)} Q_0$$

For an HII region: $L_{\text{rec line}}$ measures Q_0 of central star (cluster)

For a galaxy: idem of the entire galaxy → number of O stars
→ formation rate of O stars (since short lived)
(assumes a star formation history – major source of uncertainty)
→ total star formation rate
(assumes an Initial Mass Function – major source of uncertainty)

Recombination line luminosities of a galaxy measure
star formation rate (SFR)

Uncertainties in SFRs

$$L_{nl \to n'l'} = h\nu \, \frac{\alpha_{nl \to n'l'}(T)}{\alpha_{\mathrm{B}}(T)} Q_0$$

SFR determined via Q_0

Q_0 produced exclusively by O stars (which account for only a very small amount of mass)

The mass in SFR is dominated by low-mass stars, which do not contribute to Q_0 at all.

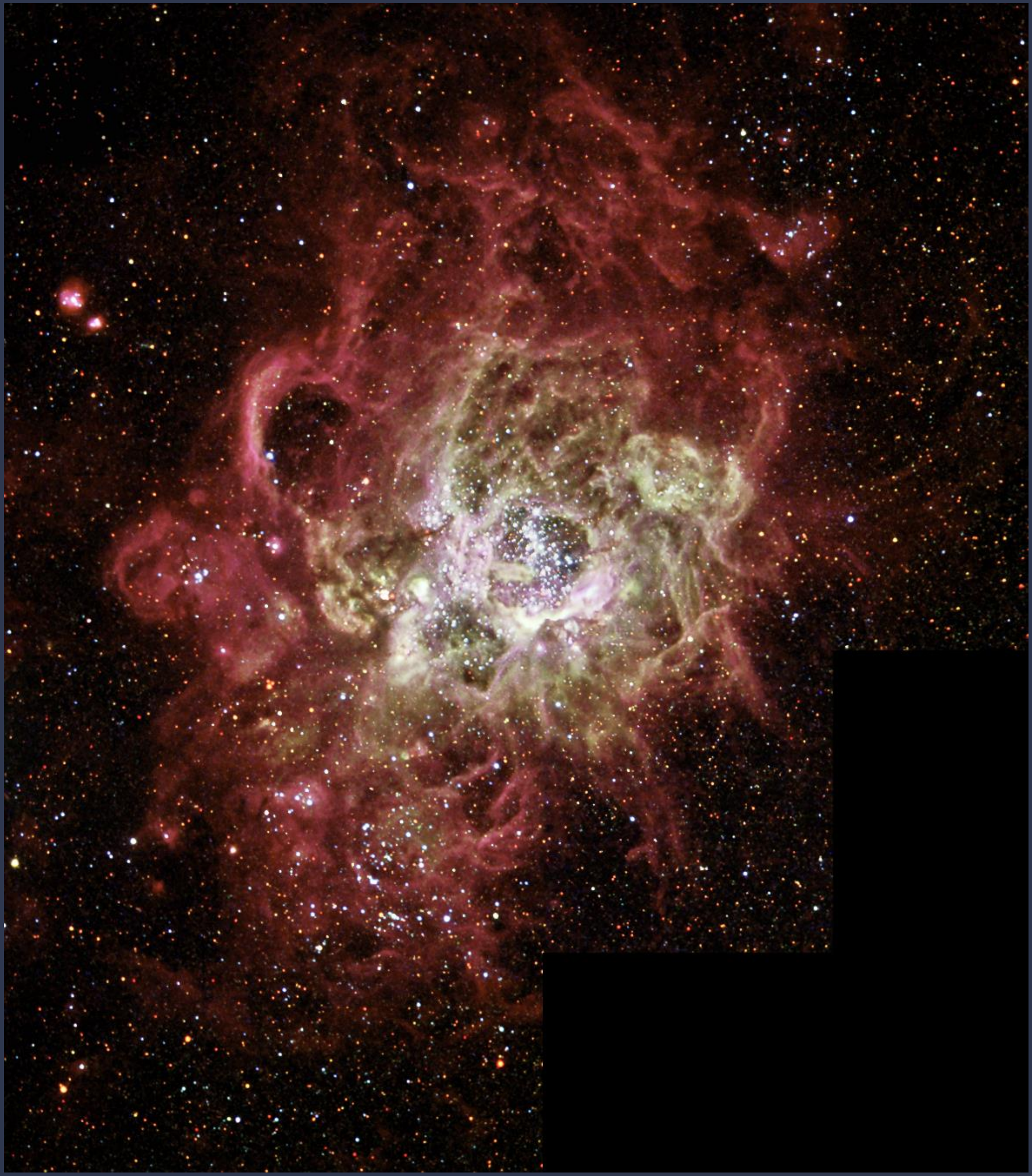
The connection is made through the IMF, which is therefore crucial in the analysis, but can only be measured (with difficulty) in the Milky Way and the Magellanic Clouds.

NGC604

Local Group Galaxy

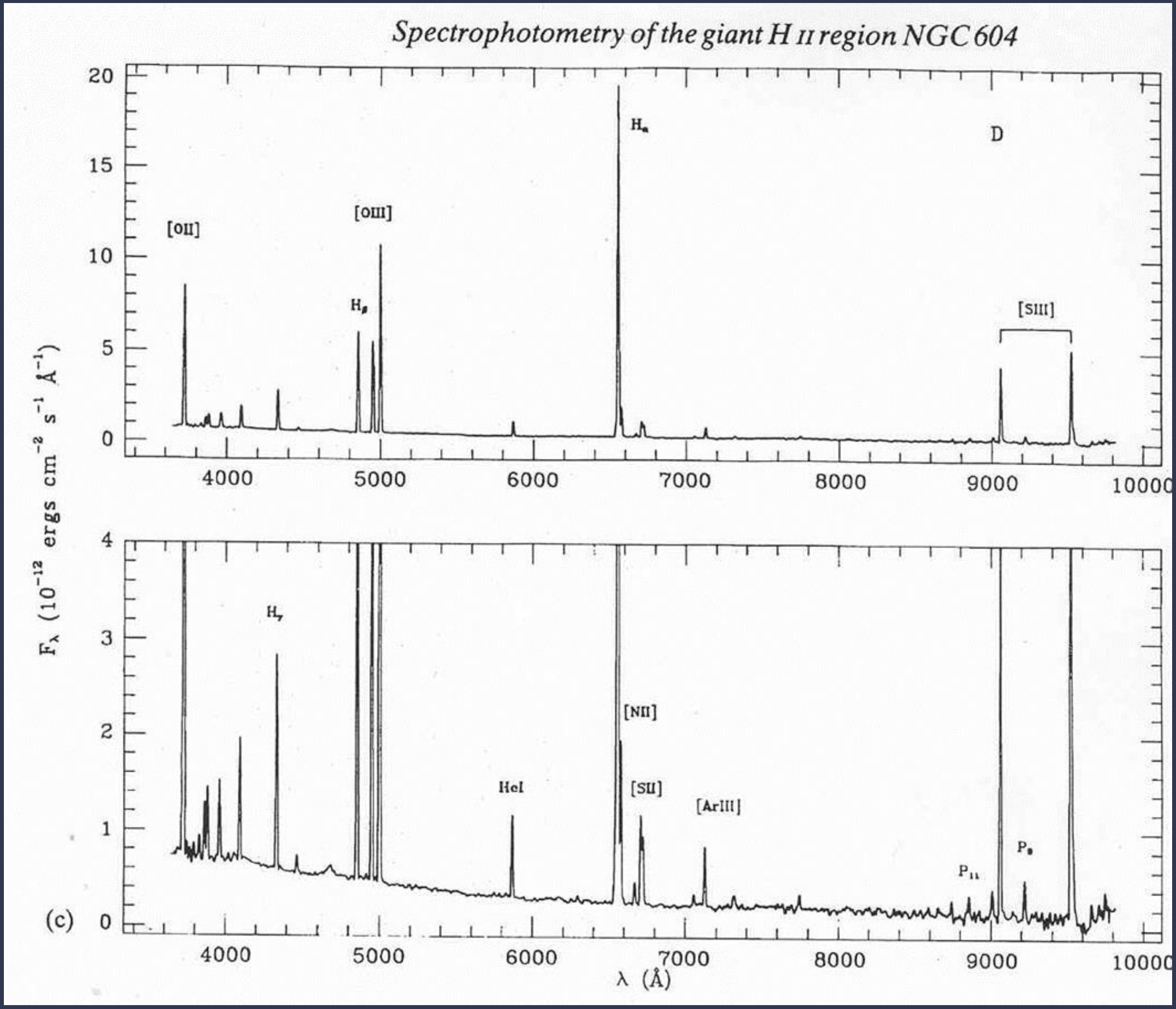
NGC604

HII Region in M33

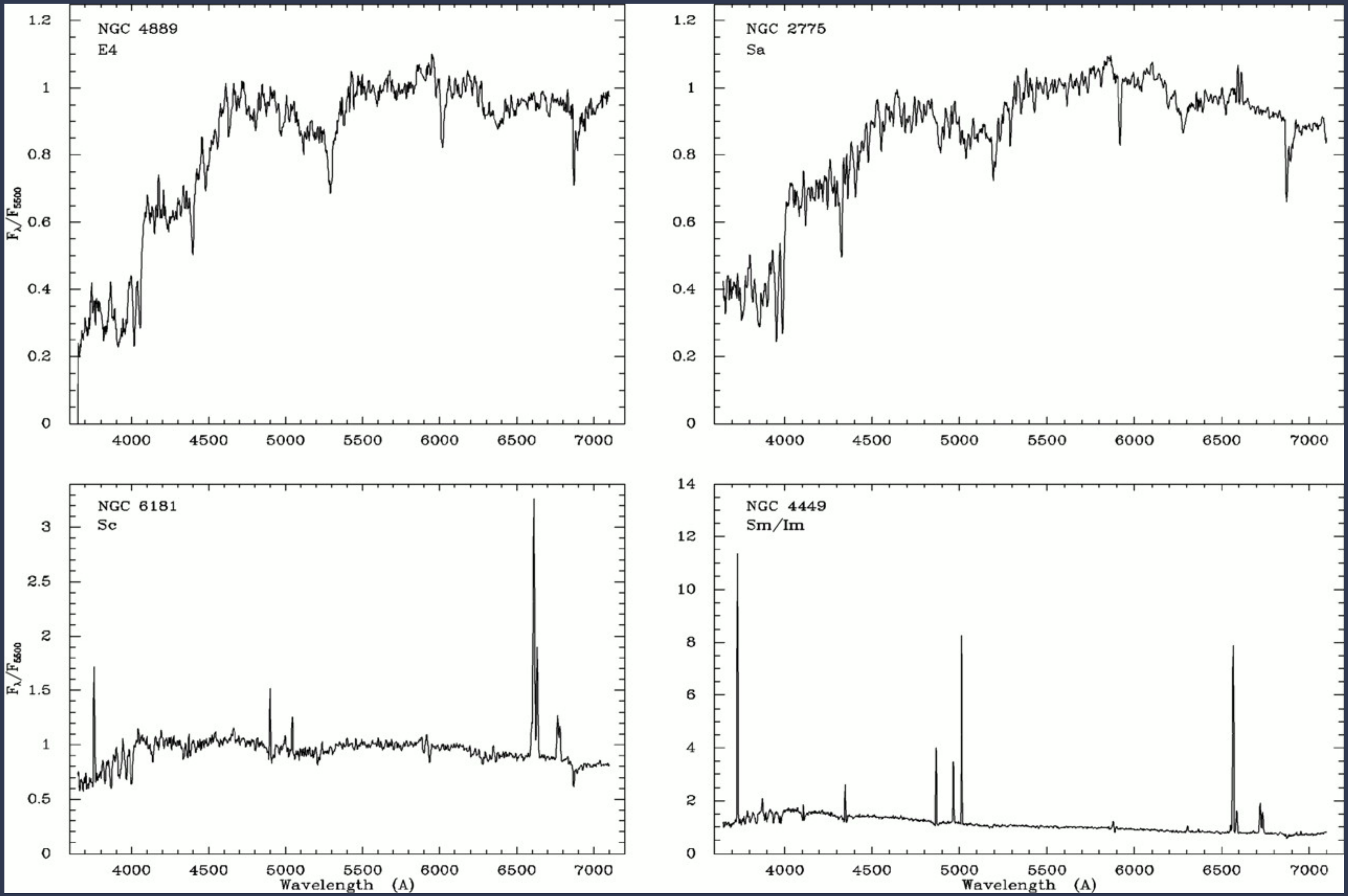


M51

HII Region spectra



Galaxy spectra



Review of Recombination Lines

- 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<<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) much more complicated: density dependence and stimulated emission
- Recombination lines (and thermal radio continuum) measure EM, Q_0 and Star Formation Rate

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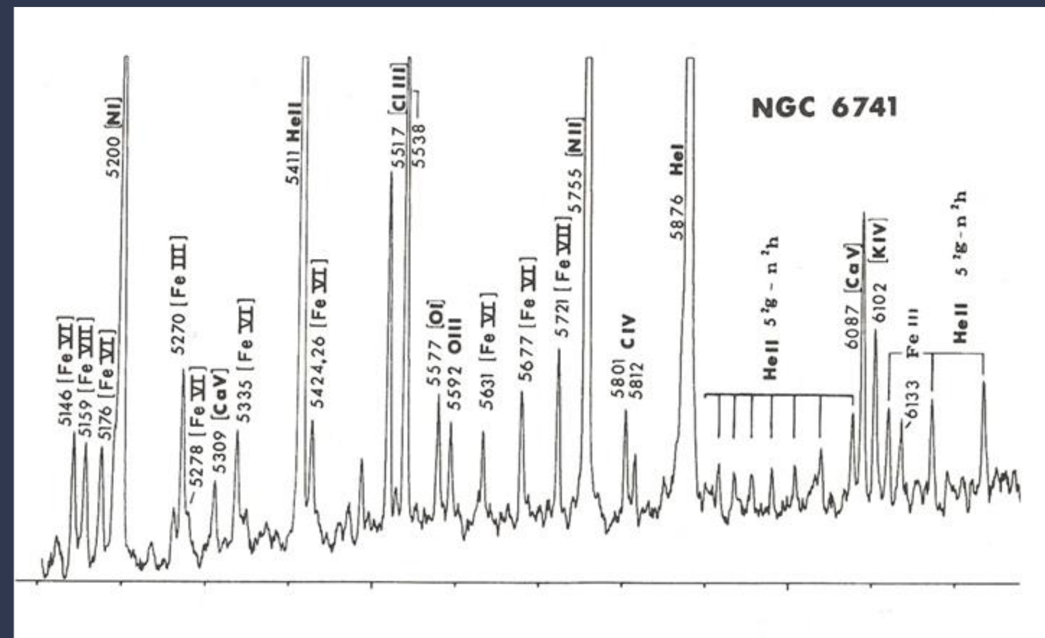
Photoionization of a nebulae with H and He

- Ionization potentials:
  - H: 13.6 eV (912 Å)
  - He: 24.6 eV (504 Å)
  - He^+: 54.4 eV (228 Å)

- Hotter stars are needed to ionize He

- Ionization potential of He^+ too high for O stars ($T_\star$ > 50,000 K needed) ⇒ He^{++} does not occur in H II regions, only in planetary nebulae

Spectrum of a Planetary Nebula



Photoionization of a nebulae with H and He

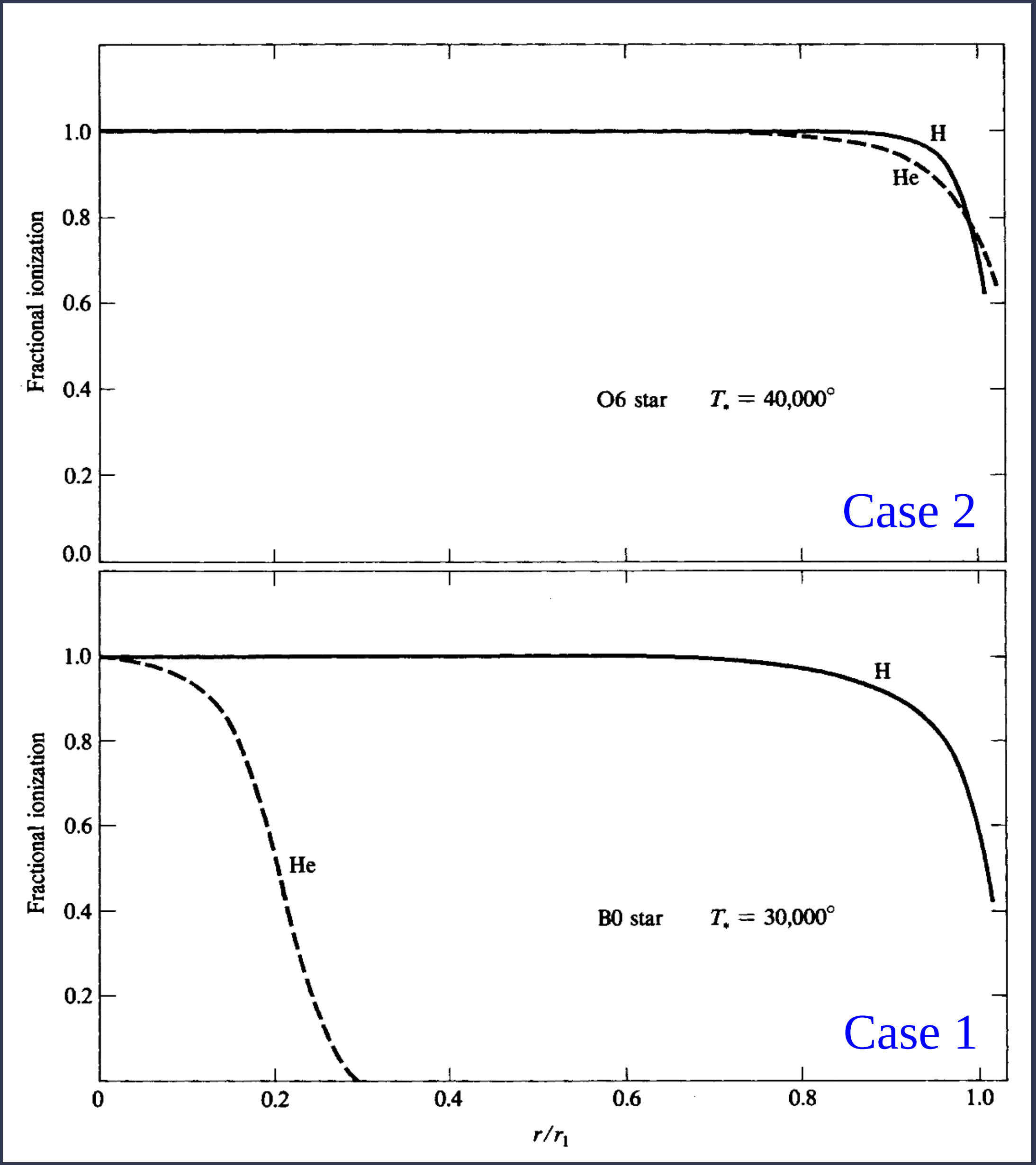
- Case 1: Spectrum of star peaks at ≈13.6 eV ➞
  Lots of photons with 13.6 eV < $h\nu$ < 24.6 eV, few photons with $h\nu$ > 24.6 eV

➞ Two Strömgren spheres:
small central He^+ zone surrounded by large H^+ region

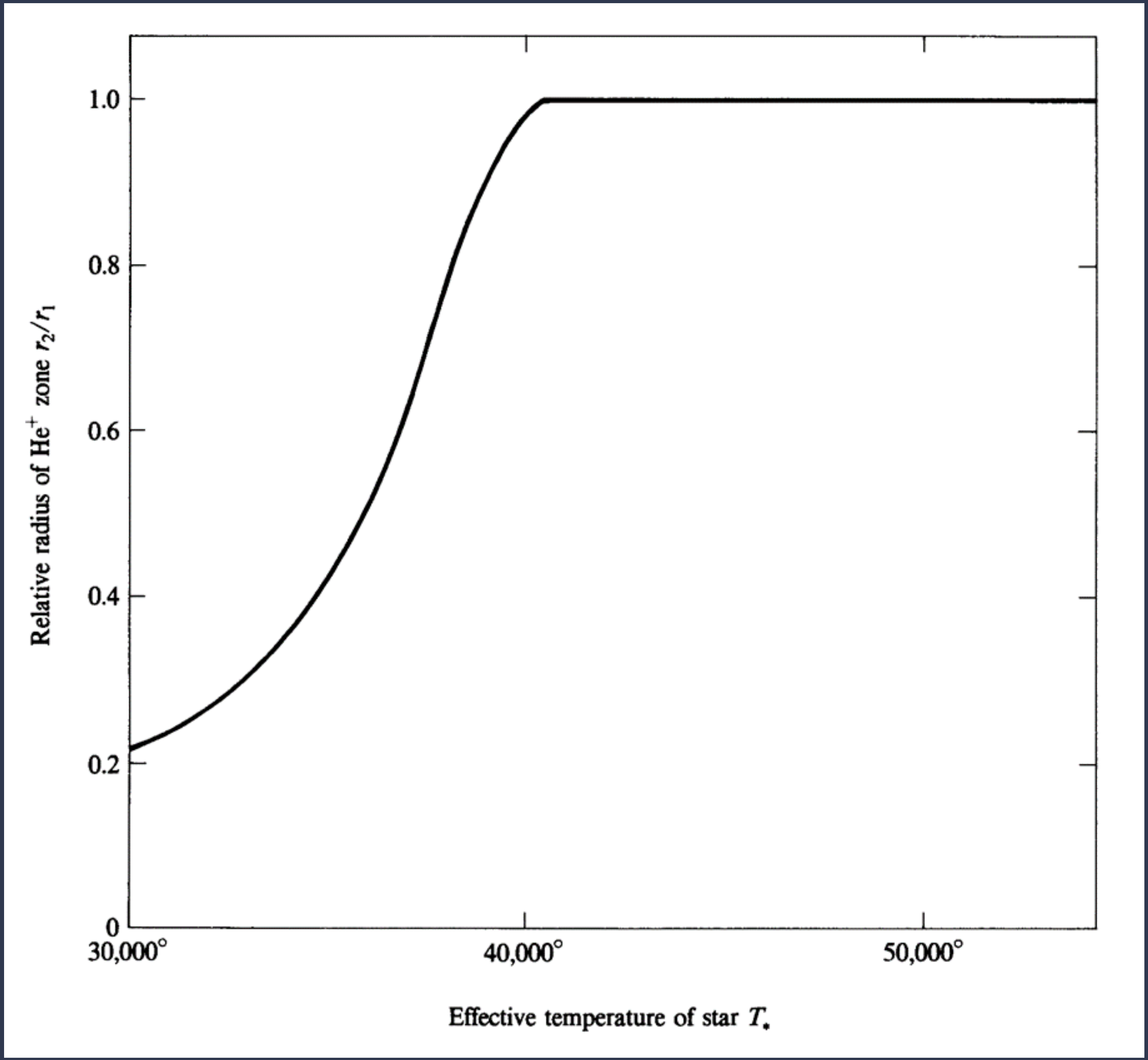
- Case 2: Spectrum of star peaks at >24.6 eV ➞
  Lots of photons with $h\nu$ > 24.6 eV

➞ H^+ and He^+ zones coincide

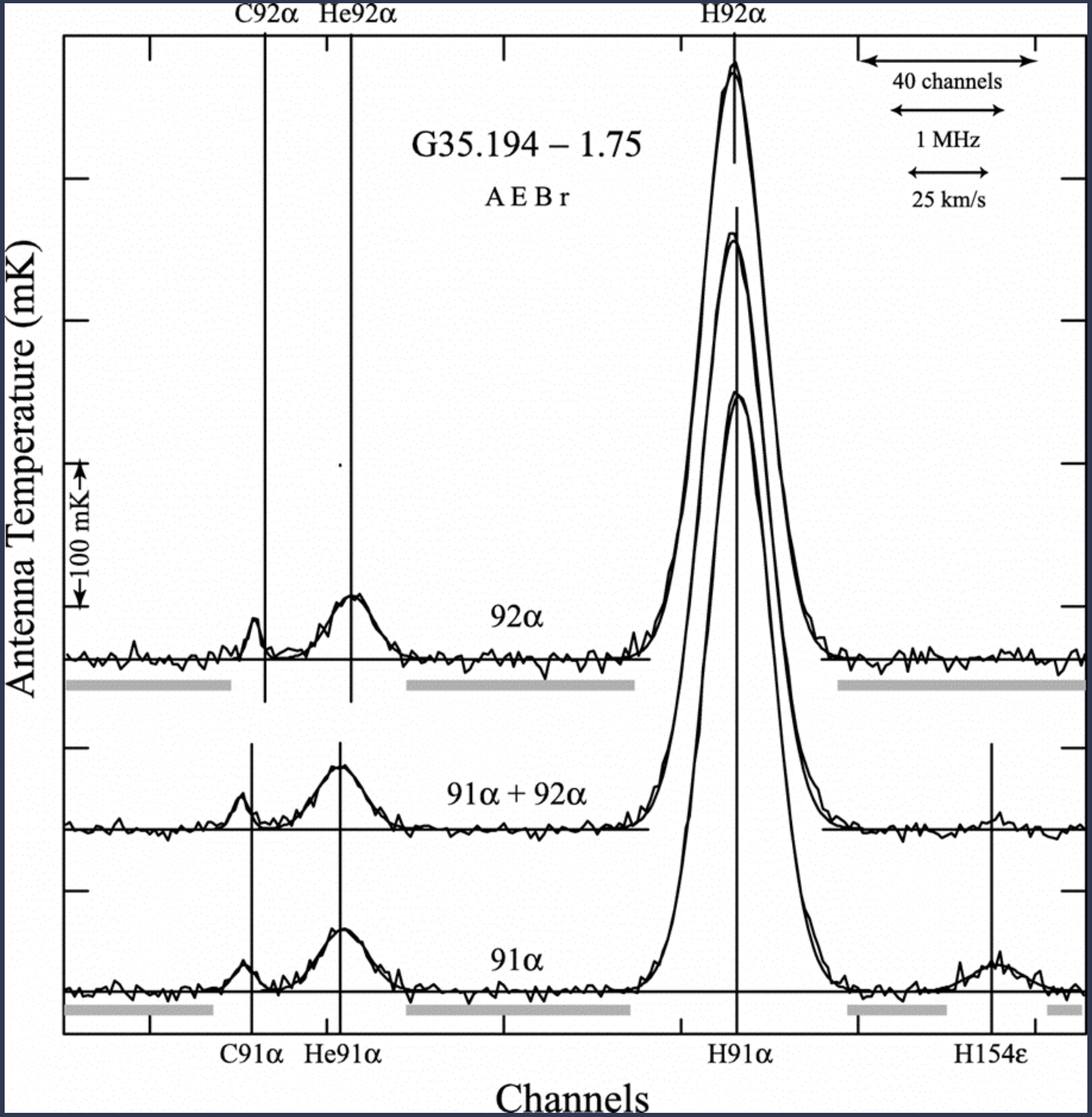
Ionization structure of H and He



He^+/H^+ radius as a function of T_*



Radio recombination lines



Ionization potentials

Element	Ion. Pot. [eV]	Element	Ion. Pot. [eV]
H	13.598	Al	5.99
C	11.26	Si	8.15
O	13.618	S	10.36
N	14.54	Ca	6.11
Na	5.14	Ca^+	11.87
Mg	7.65	Fe	7.87

Photoionization with heavy elements

- Same analysis as for He
  Ionization potential of O^{++} and He^{+} are nearly identical

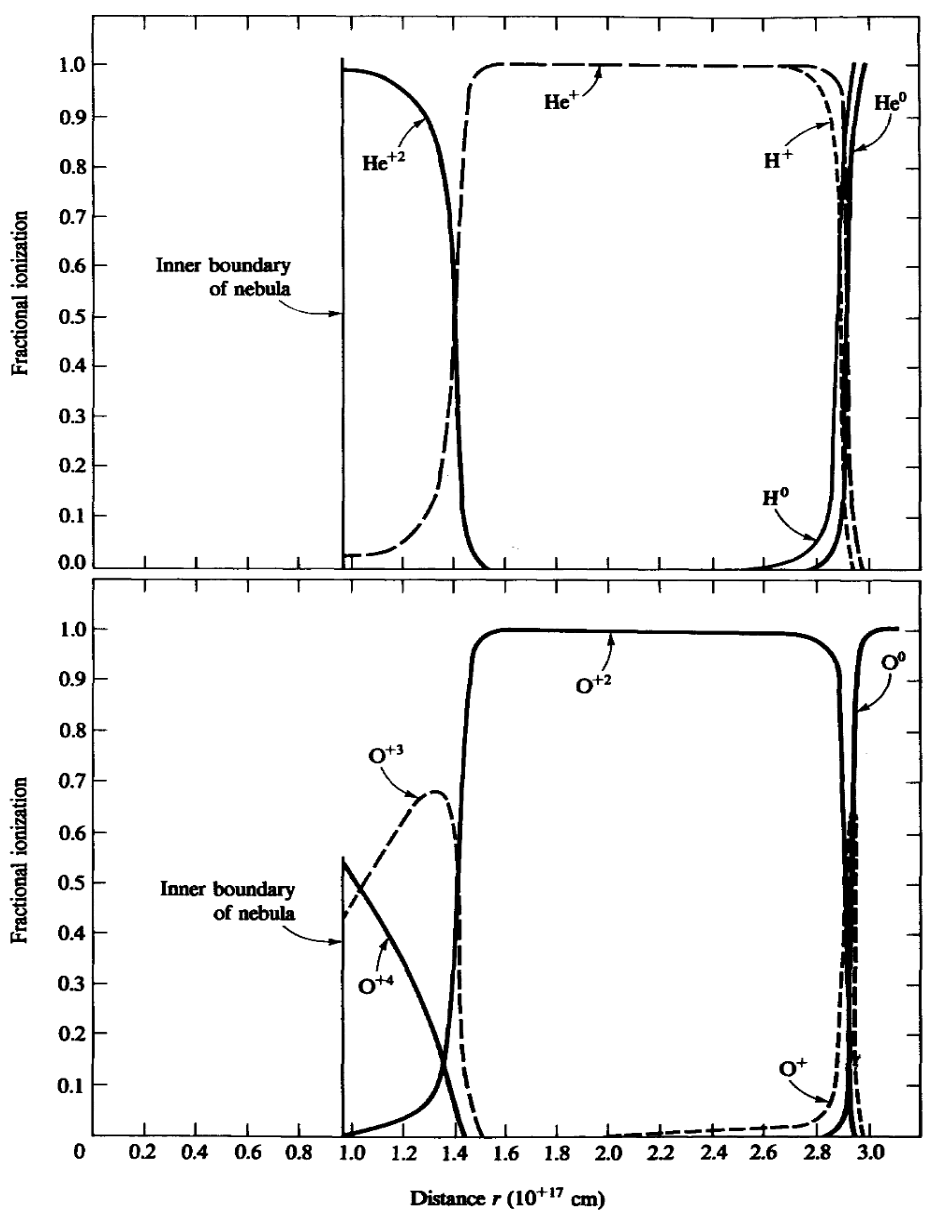
$\rightarrow$ O^{+++} zone coincides with He^{++} zone (planetary nebulae)

- Structure can be affected by charge transfer reactions:

$$X^{(m+1)+} + H \rightarrow X^{m+} + H^{+}$$

For $m \geq 2$, this process is usually fast

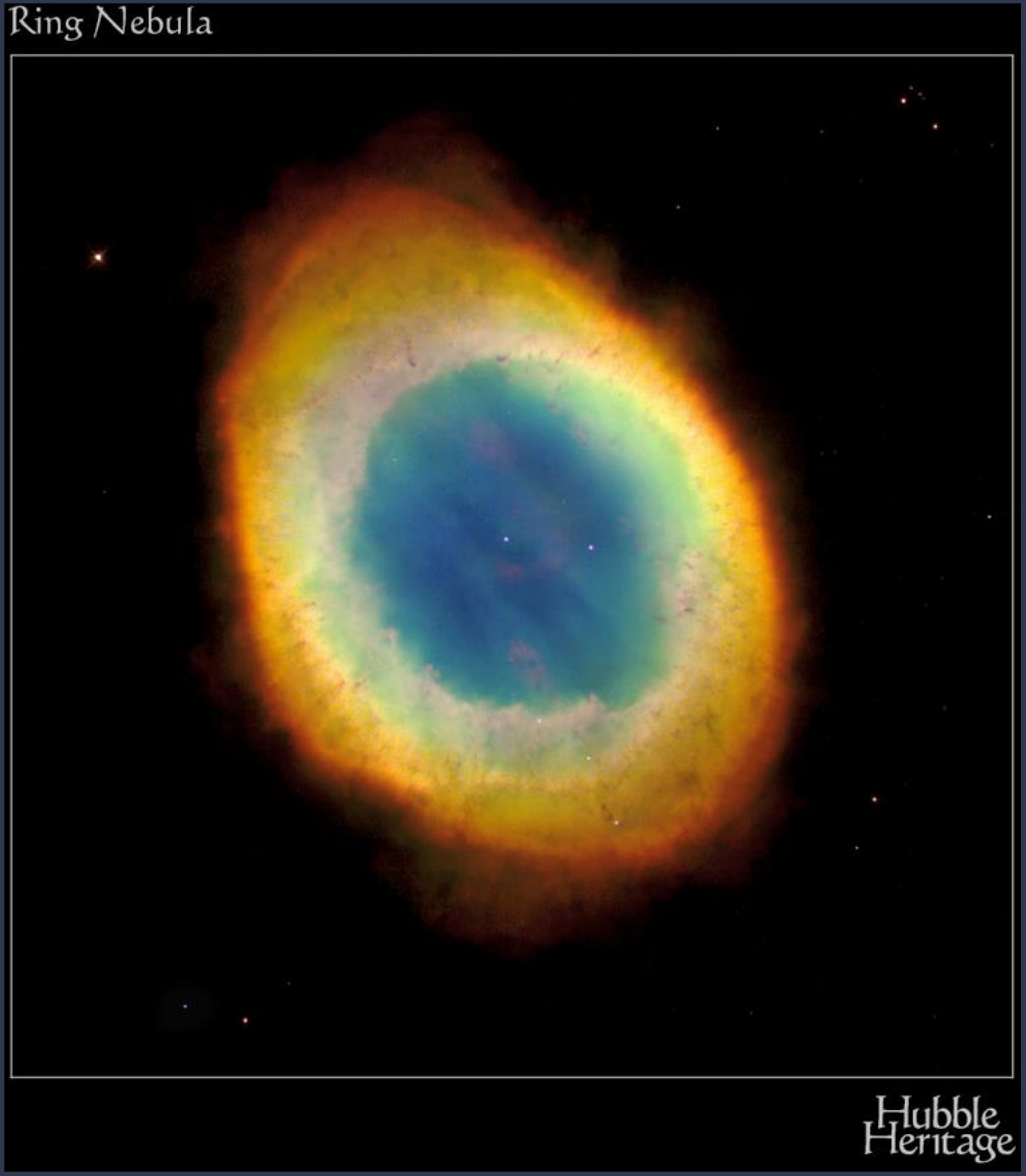
Ionization structure in a planetary nebula



Comprehensive photoionization calculation using the public code Cloudy

see www.nublado.org

Ring Nebula (M57, NGC6720)



- T_* ~ 120000 K

- Blue: HeII
- Yellow: [OIII]
- Red: [NII]

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Real HII regions (1): evolution

- Real HII regions gradually expand due to thermal pressure. Very young HII regions, born in very dense molecular clouds are very small and dense: ultracompact HII regions (UCHRs).

- Due to the expansion, a dense layer builds up at the ionization front

- Radiation pressure may be a dominant force close to the central star

Orion and the Orion Nebula

Real HII regions (2): non-uniform density

- Real HII regions are not uniform but clumpy; since almost all emission scales with EM, all probes are strongly biased towards dense regions

- Due to the expansion of the HII region, the region near the ionization front (IF) is dense and therefore bright

Orion Bright Bar Ionization Front

Real HII regions (3): boundaries

- Strömgren spheres are ionization bounded, i.e., nebula absorbs all ionizing photons from star (there is more gas than can be ionized)

- Some HII regions (including planetary nebulae) are density bounded so that some UV photons escape the nebula (there are ionizing photons left when you are out of gas)

- Some UV photons are absorbed by dust. This partially suppresses emission lines, radio continuum, radius, etc. Dust may even be dominant in dust-bounded HII regions.

Dusty HII regions

Typical cross section at 13.6 eV per H atom for dust: ~$2 \cdot 10^{-21}$ cm^2
Cf., hydrogen: ~$6 \cdot 10^{-18}$ cm^2

But: neutral fraction typically only ~0.1%, so: in a typical HII region, ~25% of Lyman continuum photons absorbed by dust.

$$R_s = \left(\frac{3Q_0}{4\pi\alpha_B n_H^2}\right)^{\frac{1}{3}} = 3.2\ \mathrm{pc}\left(\frac{Q_0}{10^{49}\ \mathrm{s}^{-1}}\right)^{\frac{1}{3}}\left(\frac{n_H}{100\ \mathrm{cm}^{-3}}\right)^{-\frac{2}{3}}$$

As *n* goes up, R_s goes down (→ compact HII region), photon density increases (closer to the star), so neutral fraction decreases even more.

→ in UCHRs, dust is dominant

For discussion

- What happens to the normal ionized gas tracers (recombination lines, thermal radio continuum) in UCHRs?

Next lecture

Collisional excitation

1. Excitation by collisions
2. Critical density
3. High and low density limits
4. Nebular diagnostics of temperature, density and other parameters