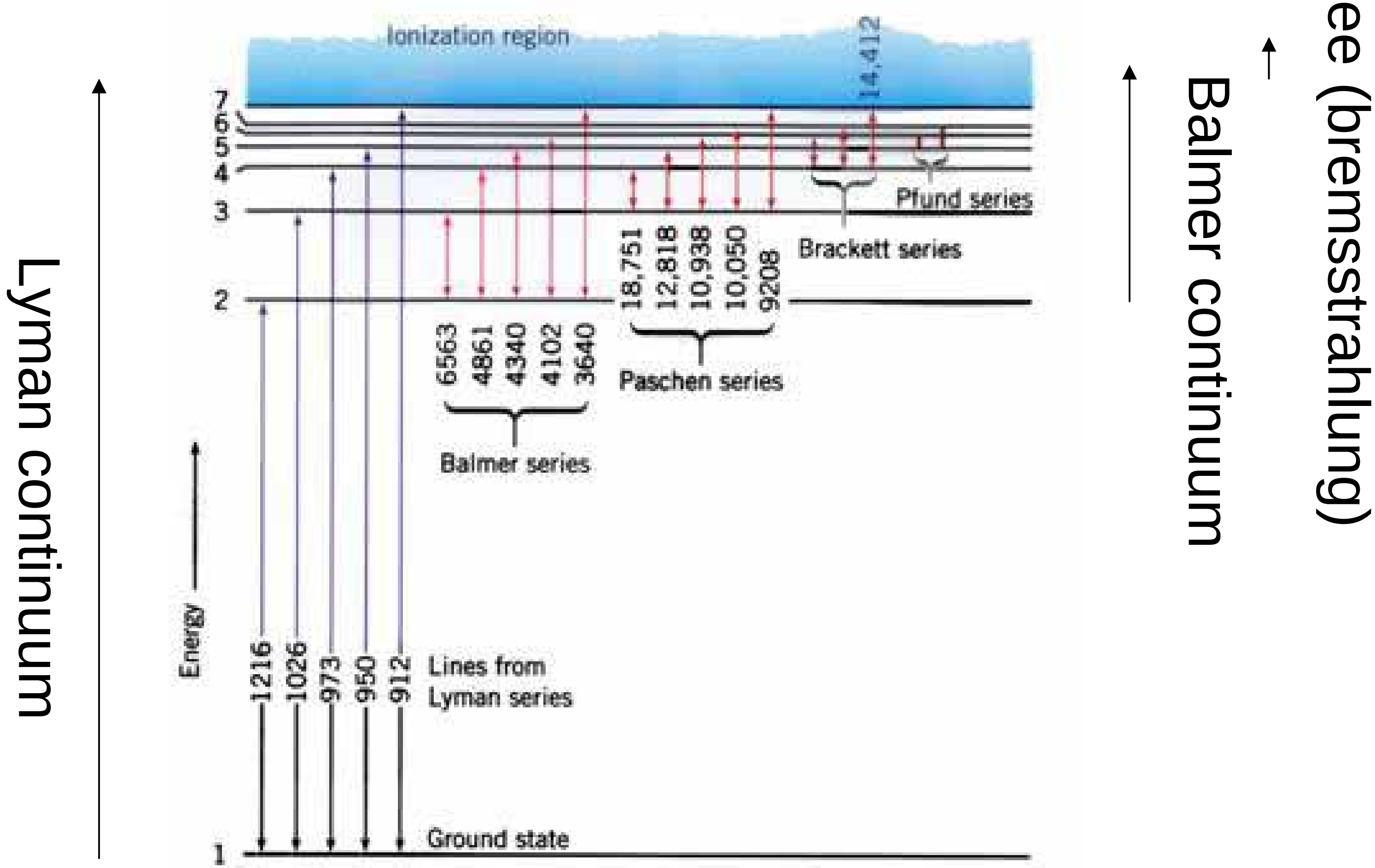
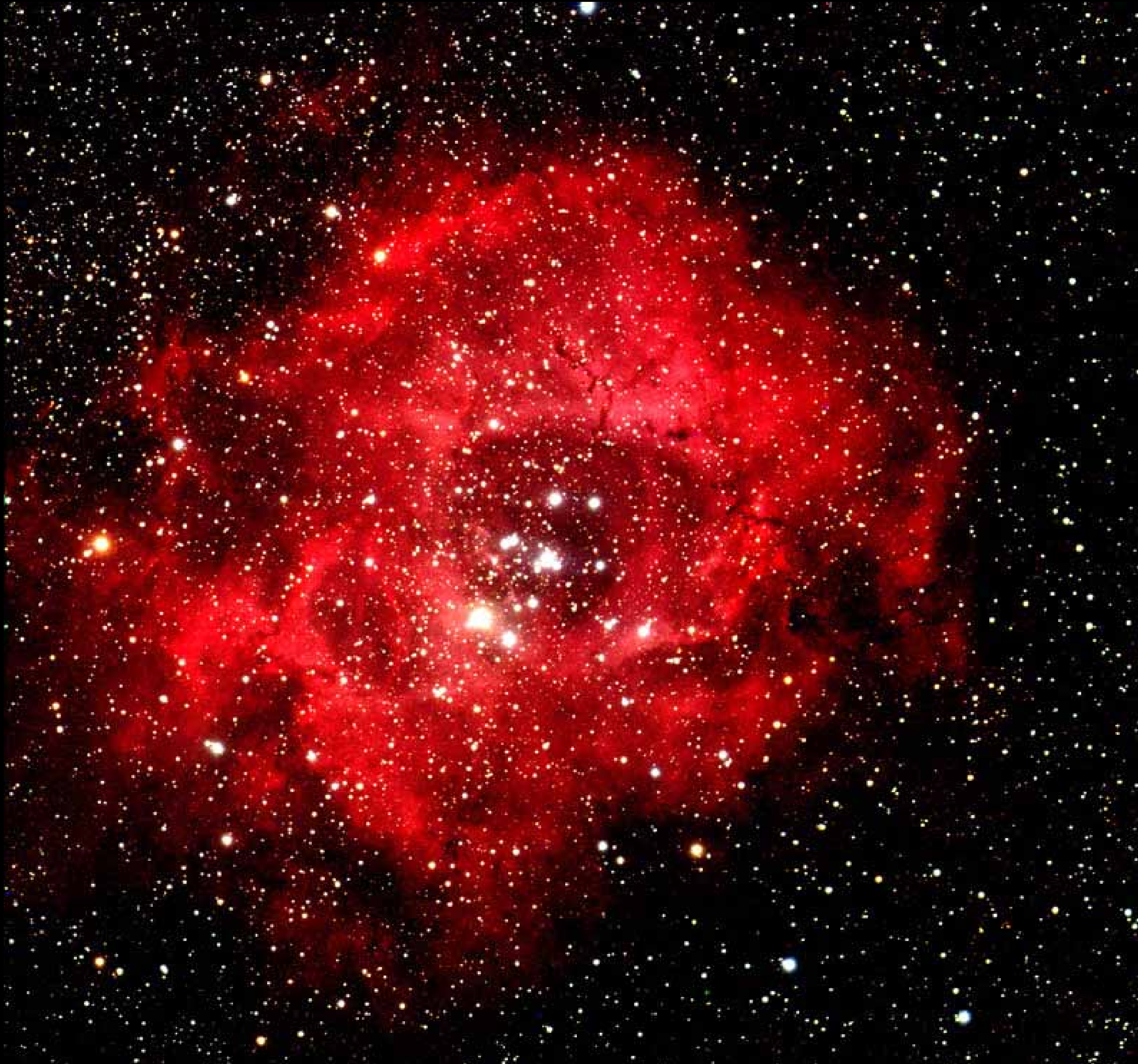
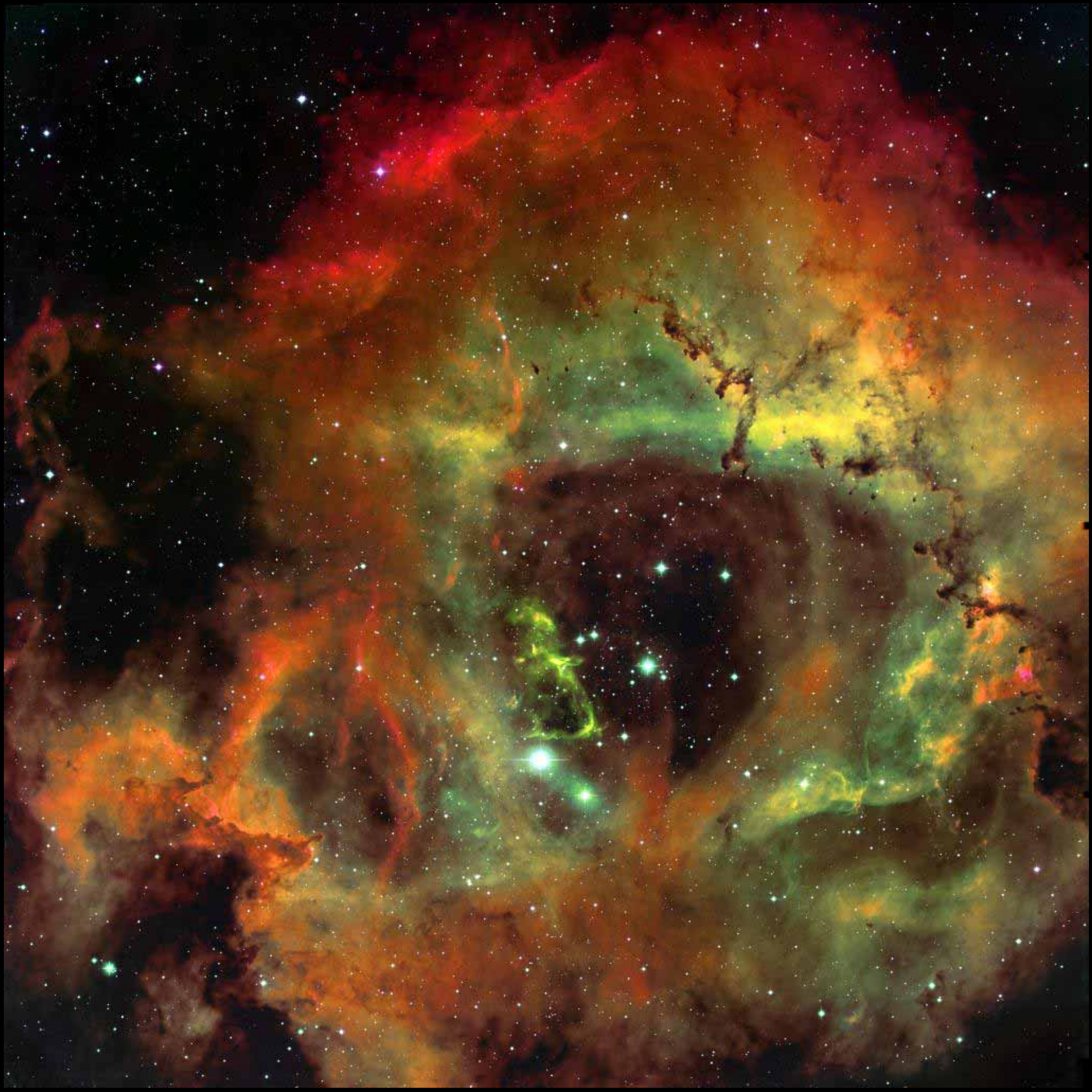
Photoionization

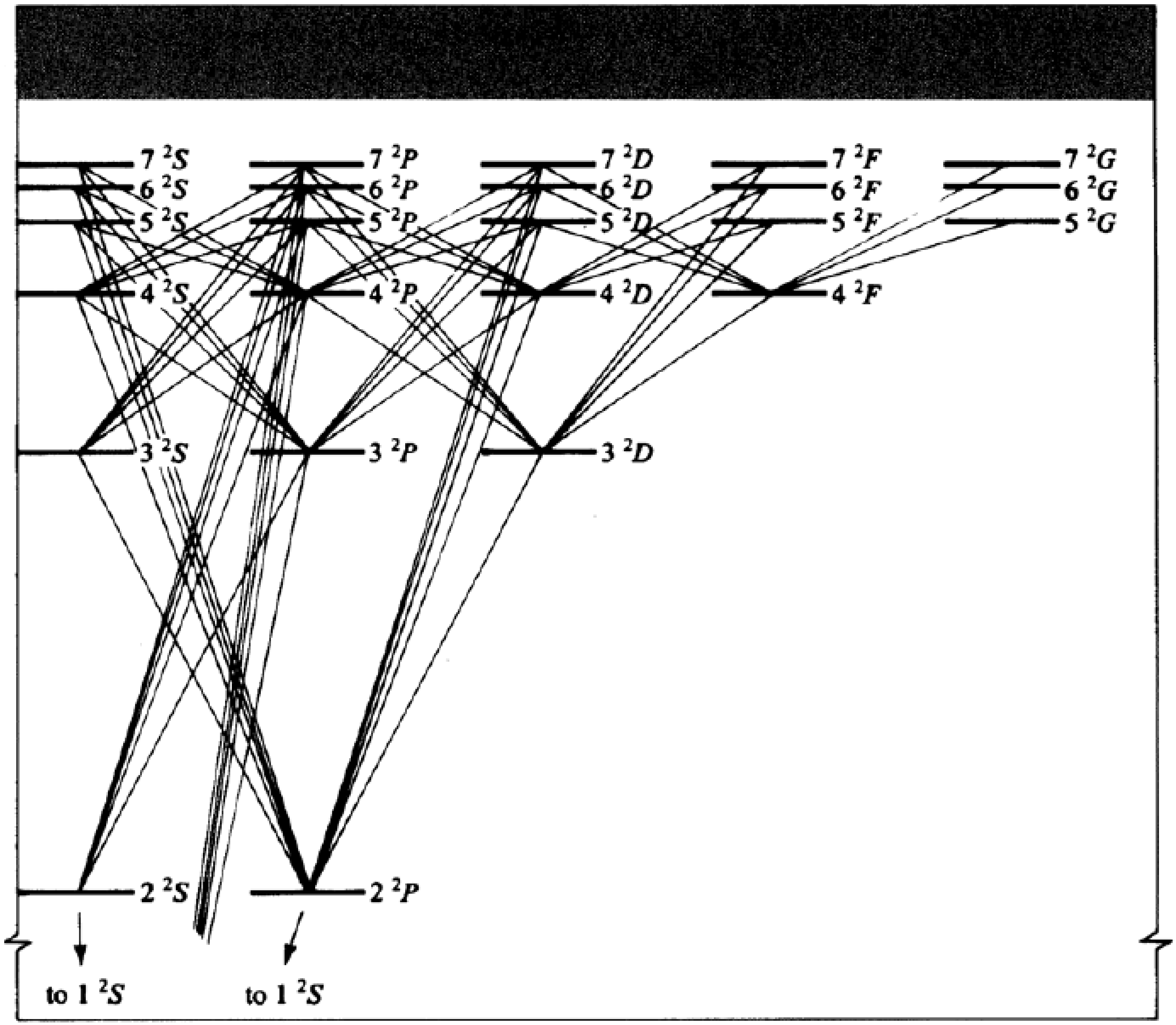


http://owcc-r-06.owcc.net/science/russo/FALL02/AST1002/Chapter%204.htm





Hydrogen spectrum --- permitted transitions



Wavelengths of important H Lines

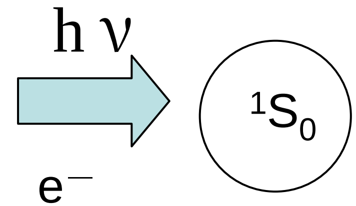
Lyα:	λ_{vac}	= 1215.68 Å	(space UV)
Hα:	λ_{air}	= 6562.73 Å	(red) 3-2
Hβ:	λ_{air}	= 4861.33 Å	(blue) 4-2
Hγ:	λ_{air}	= 4340.47 Å	(blue) 5-2
Hδ:	λ_{air}	= 4101.47 Å	(violet) 6-2
Paα:	λ_{air}	= 1.875 μm	(poor transmission)
Brα:	λ_{air}	= 4.051 μm	(difficult)
Brγ:	λ_{air}	= 2.166 μm	(in infrared K band)

Balmer lines (Hα, Hβ, Hγ, Hδ)

http://www.strw.leidenuniv.nl/~dave/ISM/lecture2.pdf

- Transition probabilities between upper state *u* and lower state *l* are characterized by Einstein *A* and *B* coefficients or related oscillator strength *f* (see appendix for def)
  - Absorption $l \longrightarrow u$: oscillator strength f_{lu}
  - Emission $u \longrightarrow l$: spontaneous emission coeff: A_{ul}
    - For transition in H: $A_{ul} \approx 10^4 \ldots 10^8\ s^{-1}$

$$E_{\mathrm{H,ion}} = 13.6 \text{ eV } (\lambda = 912\text{Å})$$



Probability of **photoionization** → photoionization cross section

$\mathrm{H} + h\nu \rightarrow \mathrm{H}^{+} + e$

$E_{kin}(e) = h\nu - 13.6 \text{ eV}$

For hydrogen-like atoms, the cross section is

$$\sigma_{\nu}^{\mathrm{ion}} = \frac{7.9 \times 10^{18}}{Z^2} \left(\frac{\nu_1}{\nu}\right)^3 g_{1f} \; [\mathrm{cm}^2], \quad \text{for } \nu > \nu_1$$

where g_{1f} is Gaunt factor ≈ 1 at optical wavelengths,

$h\nu_1 = Z^2 h\nu_0 = 13.6 Z^2$ eV

For hydrogen, $\nu_1 = 3.29 \times 10^{15}$ Hz, $g_{1f} \approx 0.8$, and a good approximation,

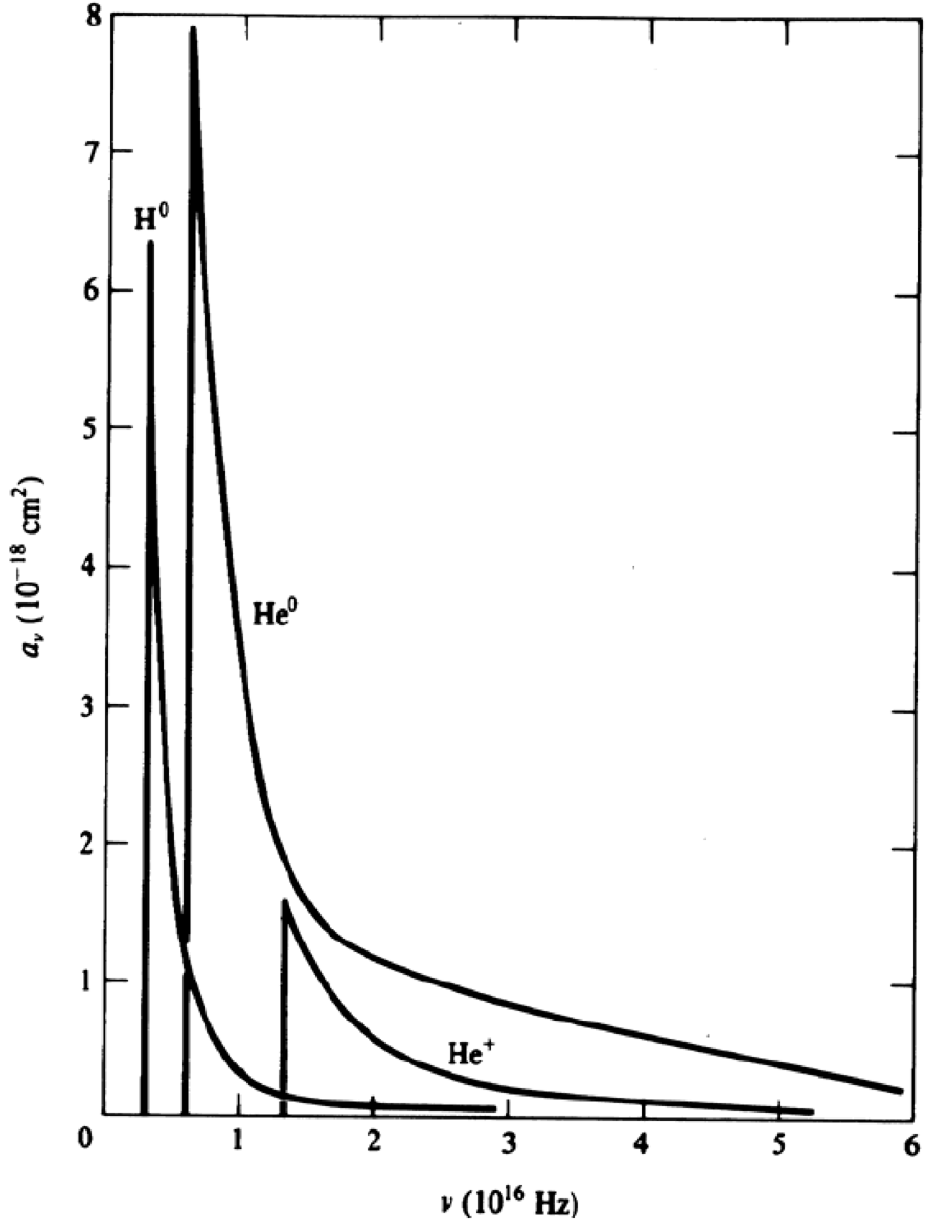
$$\sigma_{\text{ion}}(\nu) \approx 6.3 \times 10^{-18} \left(\frac{\nu_1}{\nu}\right)^3 [\text{cm}^2]$$

That is, high-energy photons, with much smaller photoionization absorption cross sections, penetrate deeper into neutral gas before being absorbed.

$$[\#\ \text{of ionization}]\ \text{s}^{-1}\ \text{atom}^{-1}\ \text{due to photons in}\ \nu\ \text{to}\ \nu + d\nu$$

$$= \sigma_\nu \frac{4\pi \bar{I}_\nu d\nu}{h\nu}$$

Photoionization Cross Sections for H, He and He⁺



Define the coefficient α, so that

$$\alpha n_e n_p = [\# \text{ of recombinations}] \text{ s}^{-1} \cdot \text{cm}^{-3}$$

$$\alpha =< v\sigma_{\text{recomb}} >$$

$$\alpha(n, L) = \int v\sigma_{nK}\, f(\vec{v})\, d^3\vec{v}$$

But recombination may end up at different levels

$$\alpha^{(n)} = \sum_{m=n}^{\infty} \alpha_m$$

$\alpha^{(1)}$: total recombination coefficient summed over all levels
$\alpha^{(2)}$" total recombination coefficient excluding captures to $n = 1$ level

αs can be computed exactly for hydrogen.

$\alpha^{(1)} = \sum_{n=1}^{\infty} \alpha_n = 6.82 \times 10^{-13}$ cm^3·s^{-1} (at 5000 K)

$\alpha^{(2)} = \sum_{n=2}^{\infty} \alpha_n = 4.54 \times 10^{-13}$ cm^3·s^{-1} (at 5000 K)

Spitzer gives $\alpha^{(2)} = 2.59 \times 10^{-3} T_4^{-0.81}$

TABLE 2.1

Recombination coefficients[a] $\alpha_{n\ ^2L}$ *for H*

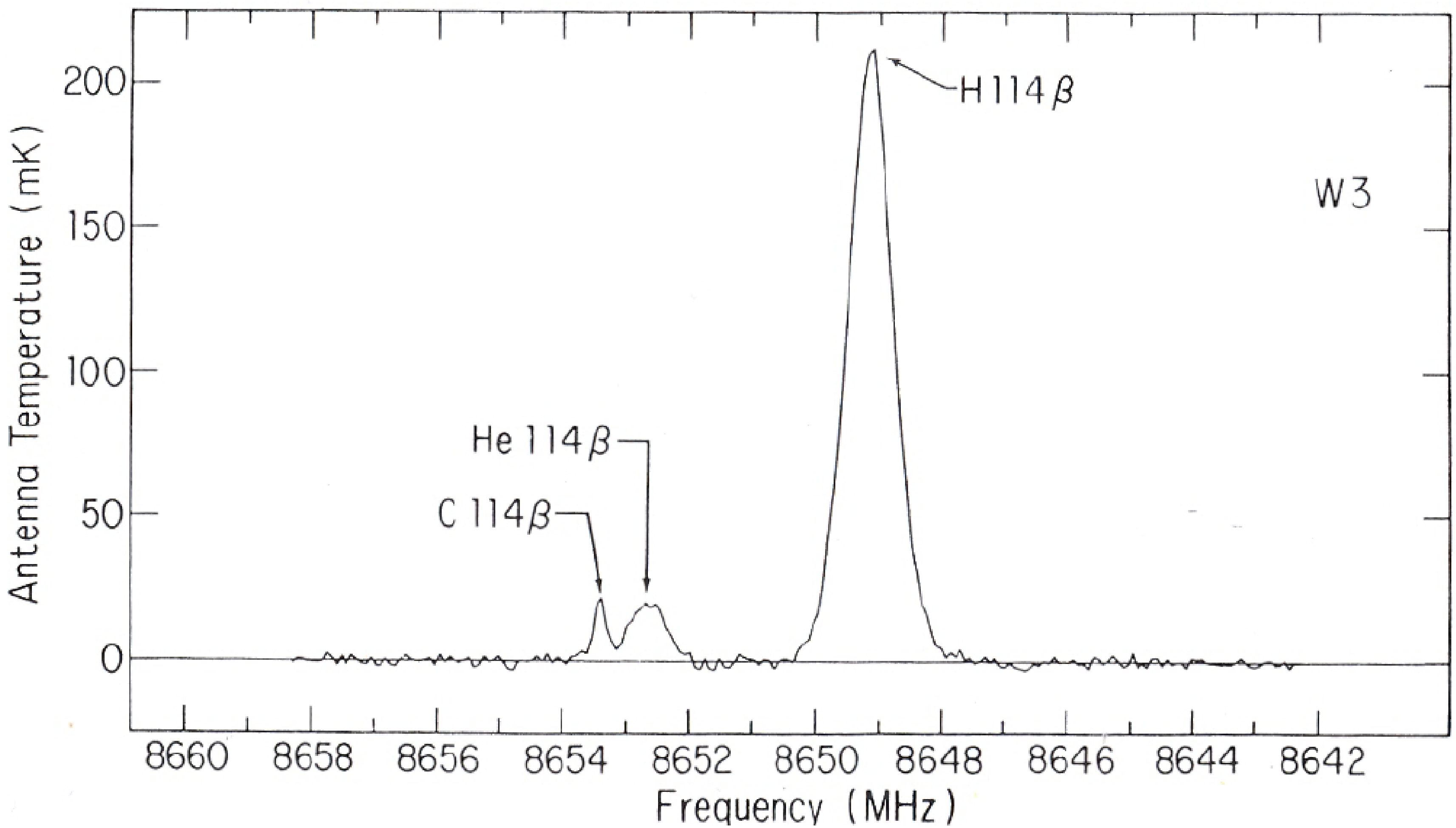
$\alpha_{n\ ^2L}$	T		
	5000° K	10,000° K	20,000° K
$\alpha_{1\ ^2S}$	2.28×10^{-13}	1.58×10^{-13}	1.08×10^{-13}
$\alpha_{2\ ^2S}$	3.37×10^{-14}	2.34×10^{-14}	1.60×10^{-14}
$\alpha_{2\ ^2P}$	8.33×10^{-14}	5.35×10^{-14}	3.24×10^{-14}
$\alpha_{3\ ^2S}$	1.13×10^{-14}	7.81×10^{-15}	5.29×10^{-15}
$\alpha_{3\ ^2P}$	3.17×10^{-14}	2.04×10^{-14}	1.23×10^{-14}
$\alpha_{3\ ^2D}$	3.03×10^{-14}	1.73×10^{-14}	9.09×10^{-15}
$\alpha_{4\ ^2S}$	5.23×10^{-15}	3.59×10^{-15}	2.40×10^{-15}
$\alpha_{4\ ^2P}$	1.51×10^{-14}	9.66×10^{-15}	5.81×10^{-15}
$\alpha_{4\ ^2D}$	1.90×10^{-14}	1.08×10^{-14}	5.68×10^{-15}
$\alpha_{4\ ^2F}$	1.09×10^{-14}	5.54×10^{-15}	2.56×10^{-15}
$\alpha_{10\ ^2S}$	4.33×10^{-16}	2.84×10^{-16}	1.80×10^{-16}
$\alpha_{10\ ^2G}$	2.02×10^{-15}	9.28×10^{-16}	3.91×10^{-16}
$\alpha_{10\ ^2M}$	2.7×10^{-17}	1.0×10^{-17}	$4. \times 10^{-18}$
α_A	6.82×10^{-13}	4.18×10^{-13}	2.51×10^{-13}
α_B	4.54×10^{-13}	2.59×10^{-13}	2.52×10^{-13}

[a] In $cm^3\ sec^{-1}$.

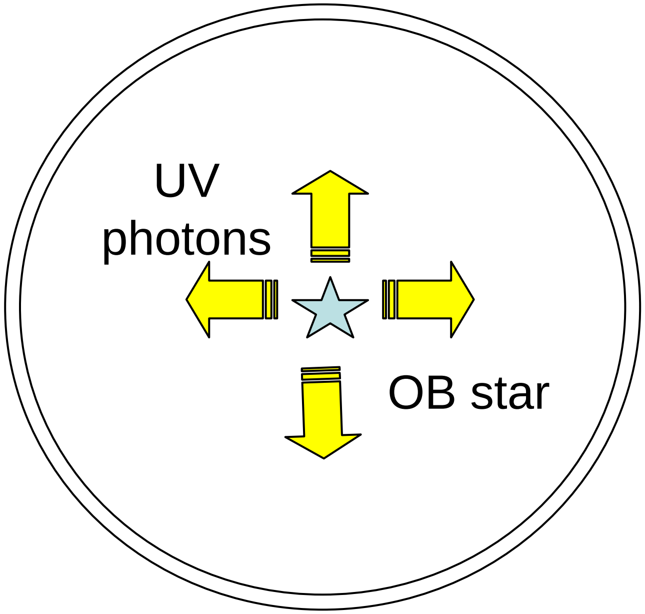
Recombination → photons

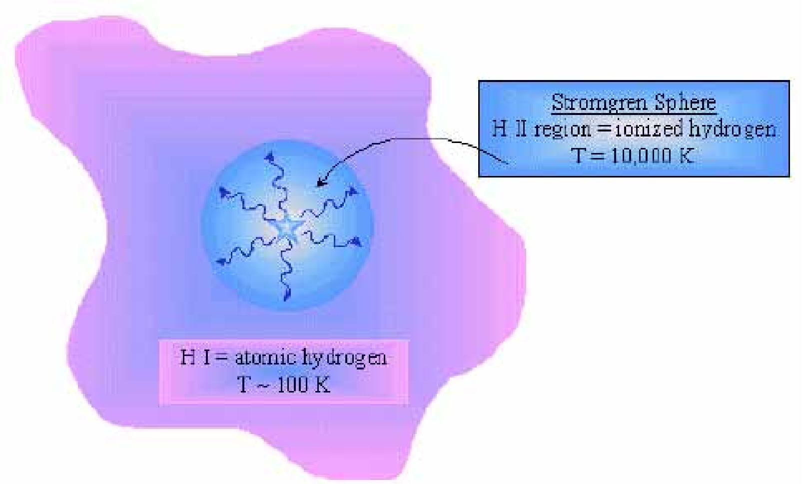
Some of the photons can ionize or excite other species

H 114 β : n=116 →114



Application: H II regions





Radiation $\lambda < 912$Å → ionization from gr state

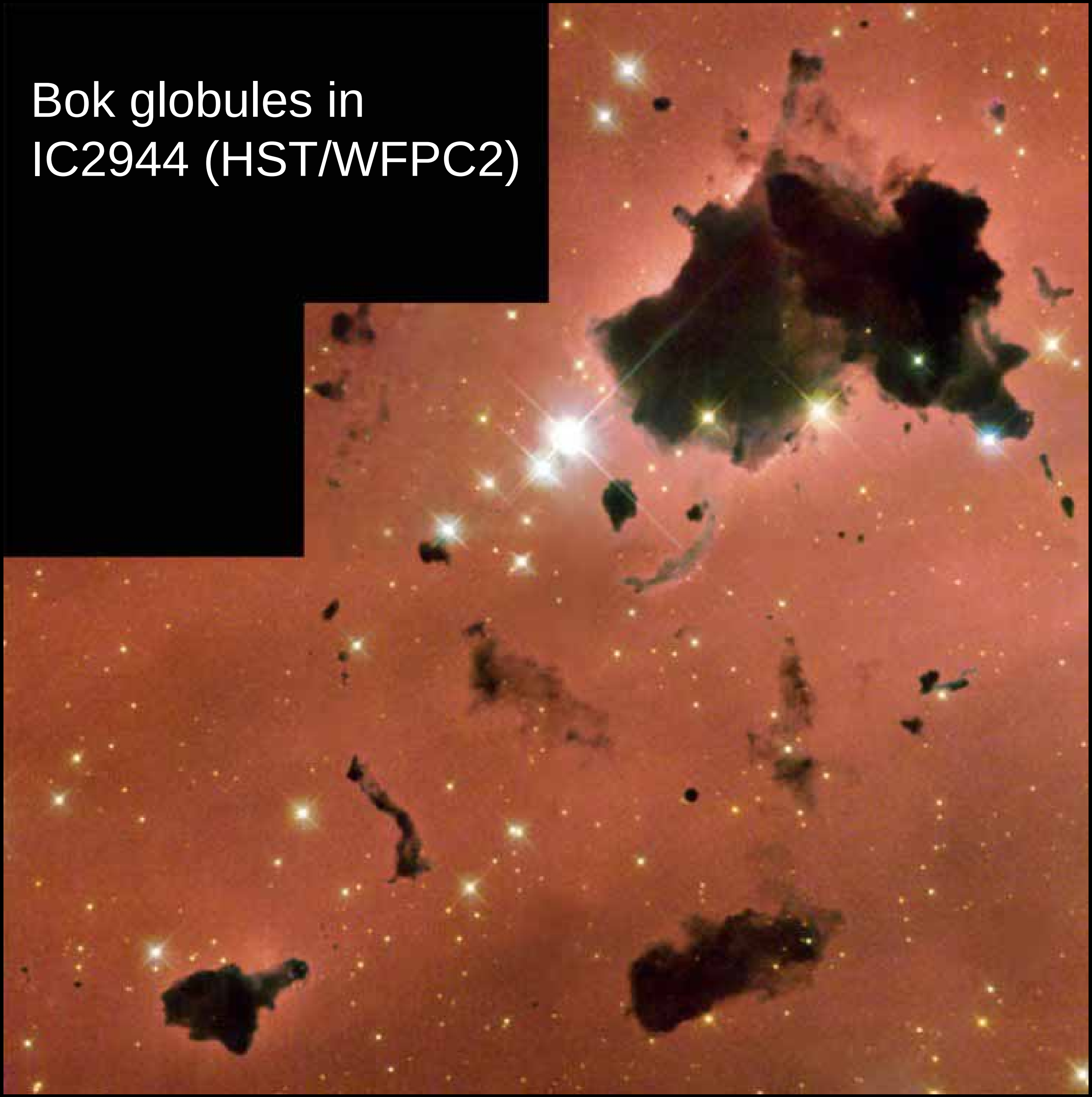
If e already in an excited state, a longer λ will do

Collisional ionization negligible in HII regions

Once ionized, e recombines with p, emitting Balmer, Paschen, Pfund lines and continua

→ e cascading → H α

Bok globules in IC2944 (HST/WFPC2)



Strings of red H II regions delineate the arms of the Whirlpool Galaxy.

Strömgren Sphere

The Strömgren radius, R_s, within which
total # of recombinations to levels except the gr. state
= total # of ionizing photons from the luminous star

Total recombinations: $\alpha^{(2)} n_e n_p \, (4\pi R_s^3/3)$

Total stellar ionizing photons $\nu > \nu_0$: $\int_{\nu_0}^{\infty} (L_\nu / h\nu) \, d\nu$

L_ν: stellar luminosity at ν [ergs s^{-1} Hz^{-1}]

$$4\pi R_*^2 \int_{\lambda=912}^{\infty} \frac{\pi B_\nu(R_*)}{h\nu} \, d\nu = \alpha^{(2)} n_e n_p (4\pi R_s^3/3)$$

Within R_s, ionization is complete, $n_e \approx n_p \approx n_H$

Outside R_s, $n_e \approx n_p \approx 0$

Designate the LHS (# of Lyman photons) as L^*_{912}, we get

$$L^*_{912} = 4\pi R_s^3 \alpha^{(2)} n_H^2 / 3$$

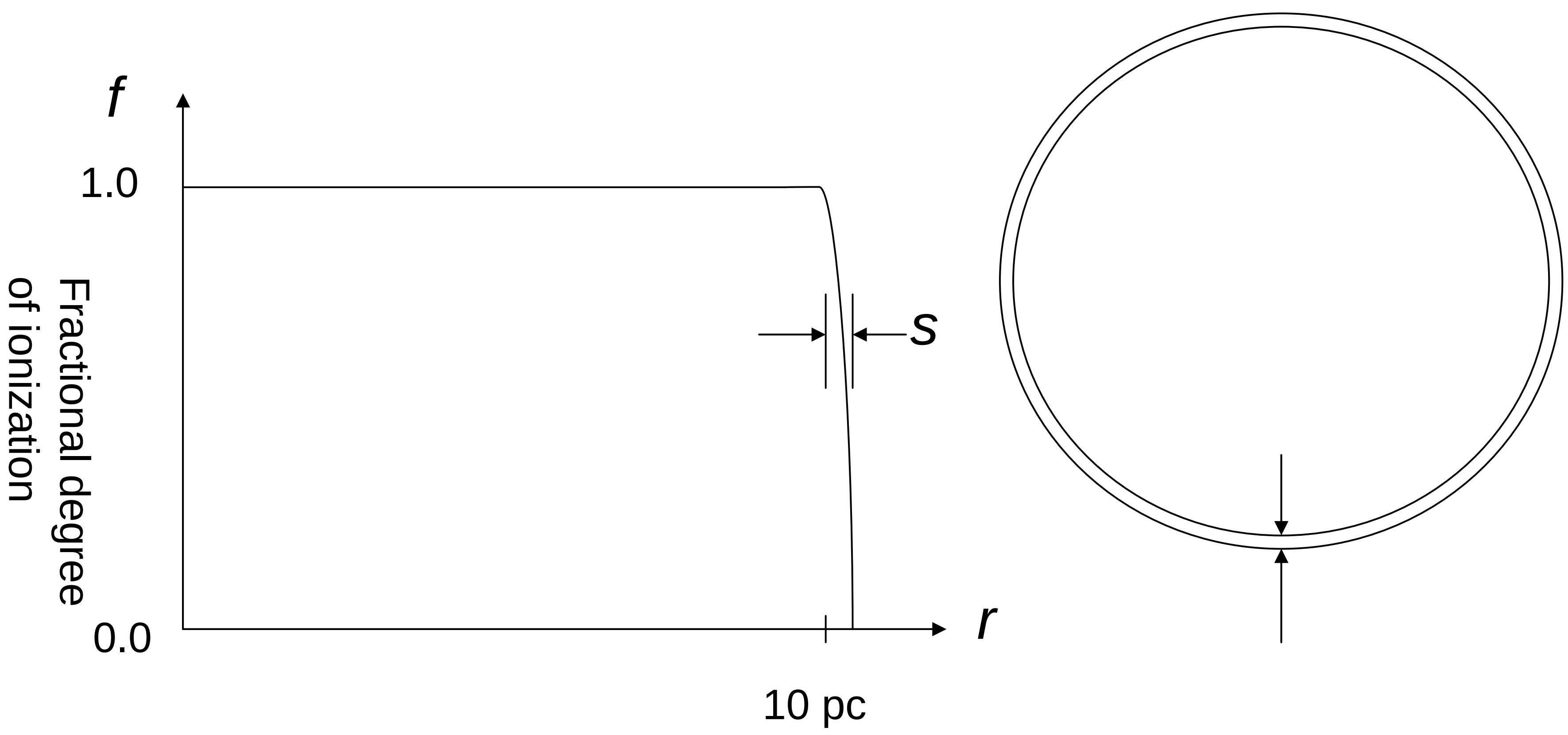
$$\boxed{R_s = \left(\frac{3L^*_{912}}{4\pi\alpha^{(2)} n_H^2}\right)^{1/3}}$$

$$L^*_{912} \approx 5 \times 10^{42} \exp(3.2 \times 10^{-4}\ T_*)$$

$$R_s \approx 0.62\ n_H^{-2/3} \exp(1.07 \times 10^{-4}\ T_*)\ \mathrm{pc}$$

Take $T_* = 40,000$ K (i.e., O6 V), $n_H = 10$, $R_s \approx 1$ pc, then $R_s \approx 10$ pc

How thick is the transition zone (s)?



In the transition zone, $\tau = \sigma_\nu^{\rm ion}\, n_H\, s \approx 1$

$$s = \frac{1}{\sigma_\nu\, n_H}$$

Given $\sigma_{\nu_{912}} = 6.3 \times 10^{-18}$ cm^2, $n_H = 10$ cm^{-3},
$s \approx 0.005$ pc $<< 10$ pc

The boundary of an H II region is very sharp!

Spectral Type	T_* [K]	$R_s (n_e n_p)^{1/3}$ [pc cm^{-2}]
O5	47,000	110
O9	34,500	38
B1	22,600	4.4

Note: The above assumes no dust absorption;
otherwise $R_s \downarrow$

Av (mag)	0.1	0.5	1.0	2.0	5.0	10.0
R’s/Rs	0.91	0.70	0.56	0.42	0.25	0.15

- He can also be ionized, $\lambda < 506$ and < 208 Å
- Stars very hot, T* > 10^5 K
- Ionization Application --- **Zanstra Method**
  If all $\lambda < 912$ Å photons absorbed by H atoms in the nebula
  Each UV photon
  → 1 Ly photon (absorbed and re-emitted)
  + 1 Balmer photon (escaped readily)
- So, # of Balmer photons = # of $\lambda < 912$ Å photons → all energy radiated by the star
  → T_*