Emission Nebulae

(i) Photoionization

A hot star,
$T > 10^4$ K

UV ⇝

For $h\nu > 13.6$ eV
If $\lambda < 91.1$ nm → ionization of H
If $\lambda < 50.4$ nm → ionization of He

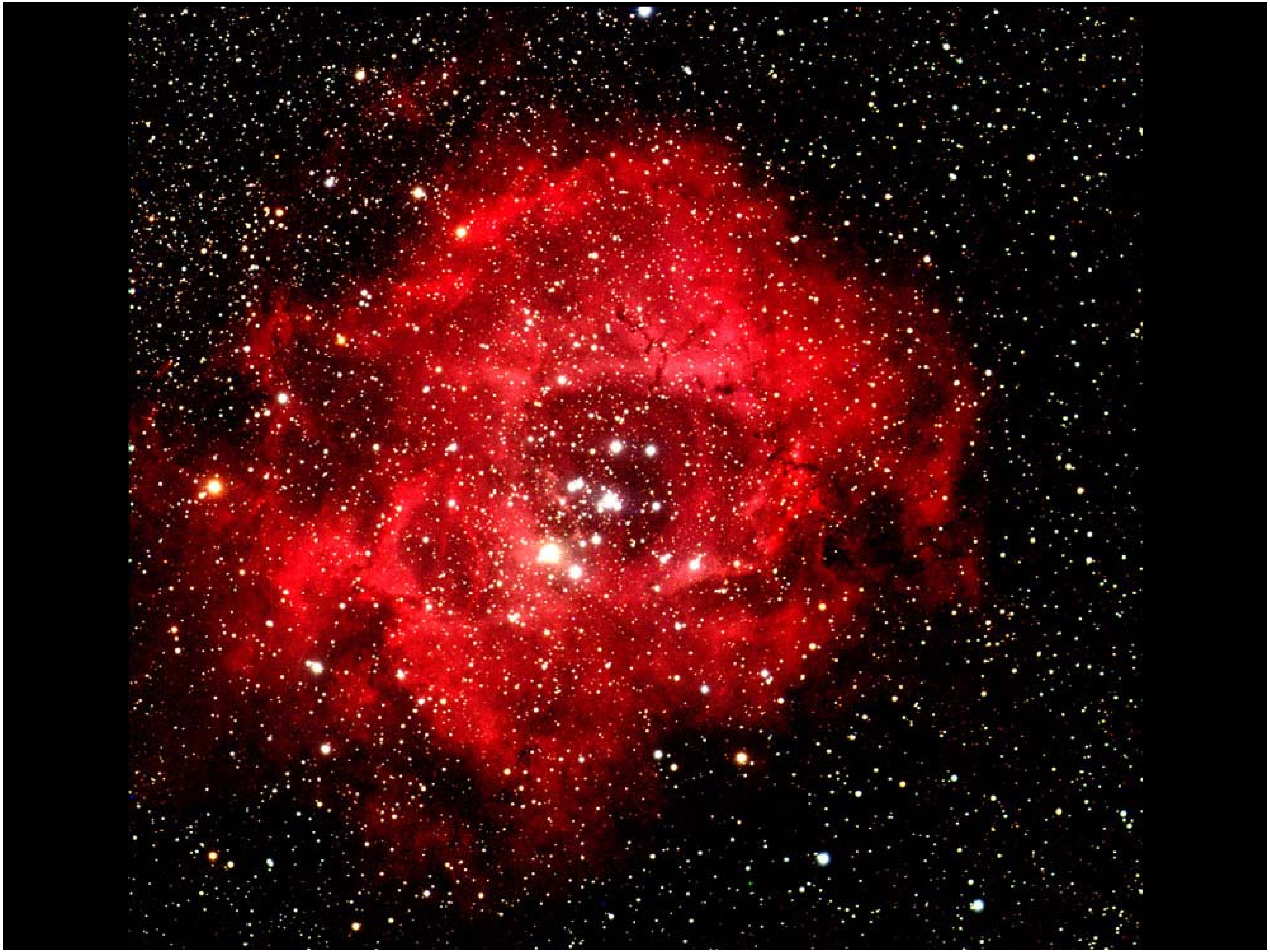
This produces lots of e- to excite collisionally low-lying levels of ions; electrons eventually drop back to the ground levels via cascade transitions

→ **Recombination lines** of H, He I, He II and other ions

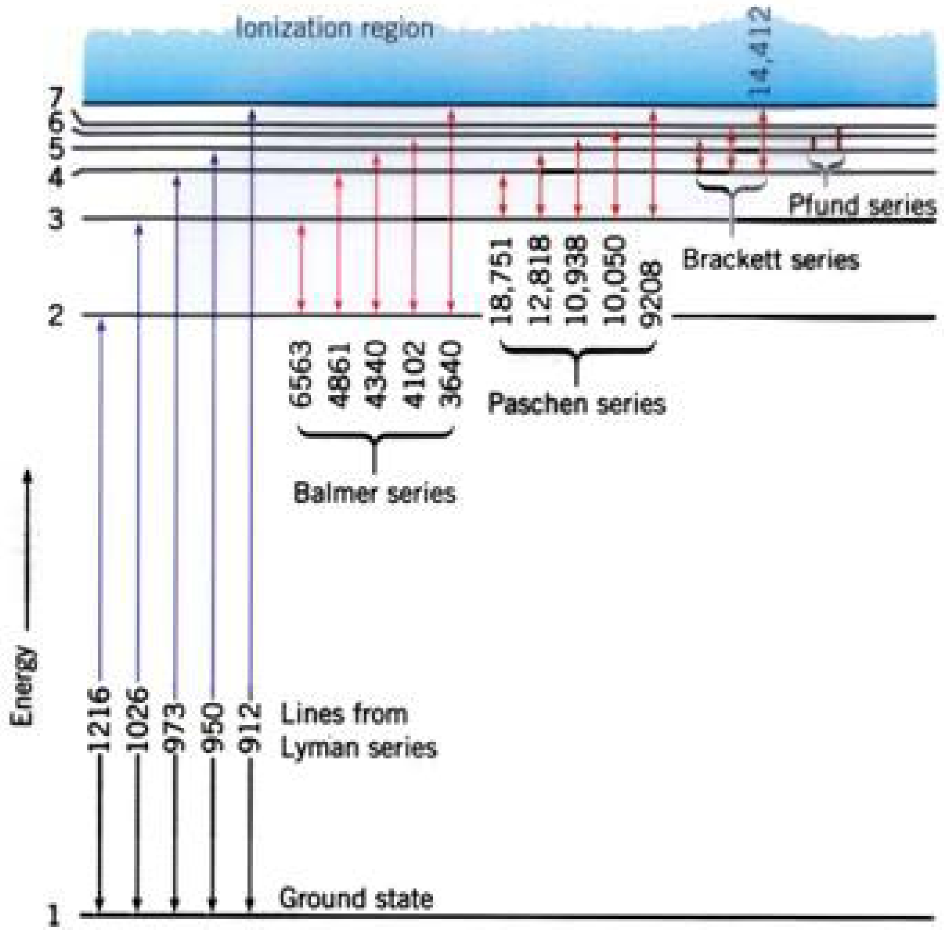
(ii) Fluorescence

For example, He II λ 30.38 nm line photon absorbed by O III → Emission of a number of O III lines

(iii) Forbidden lines



Photoionization



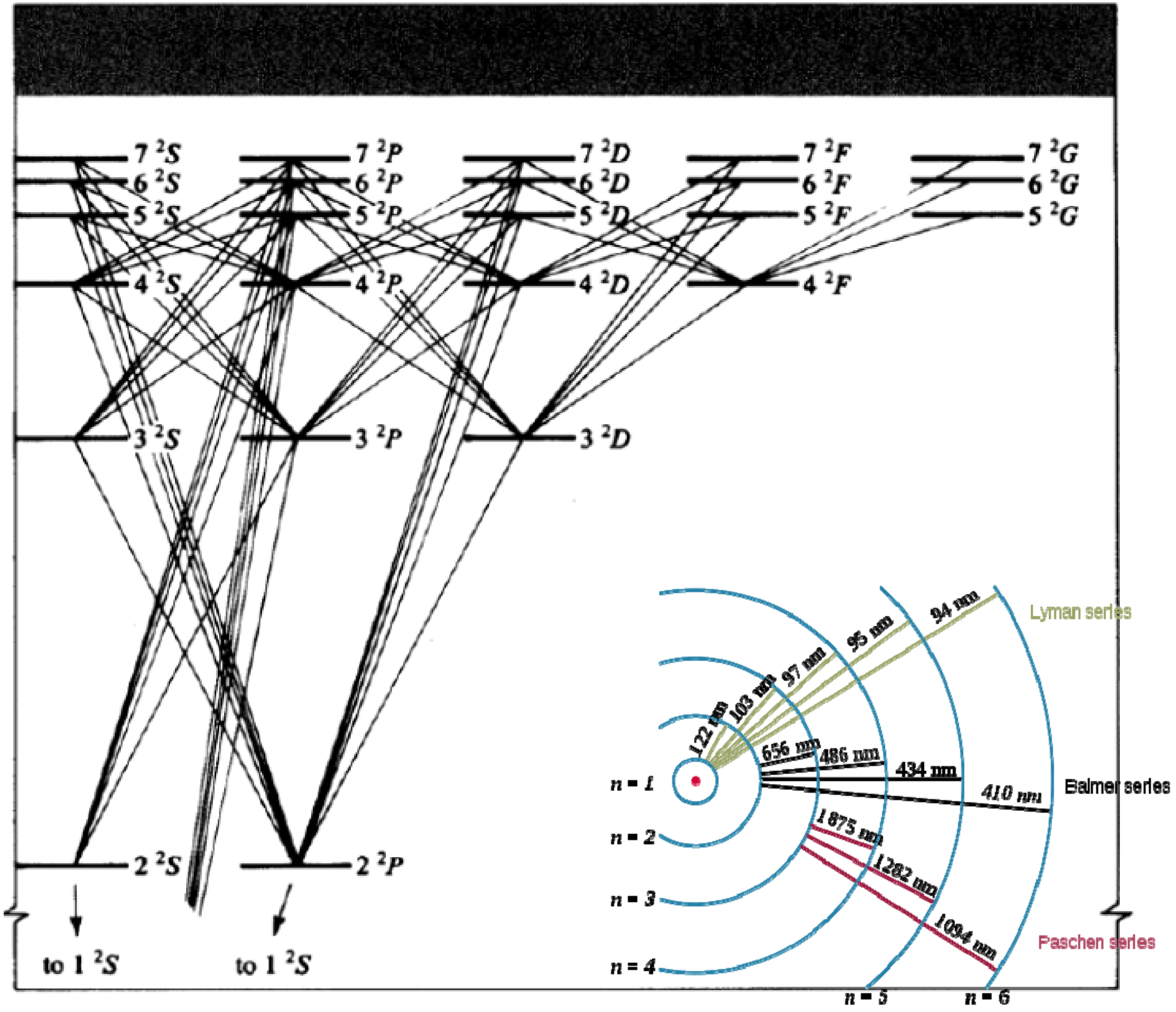
Lyman continuum

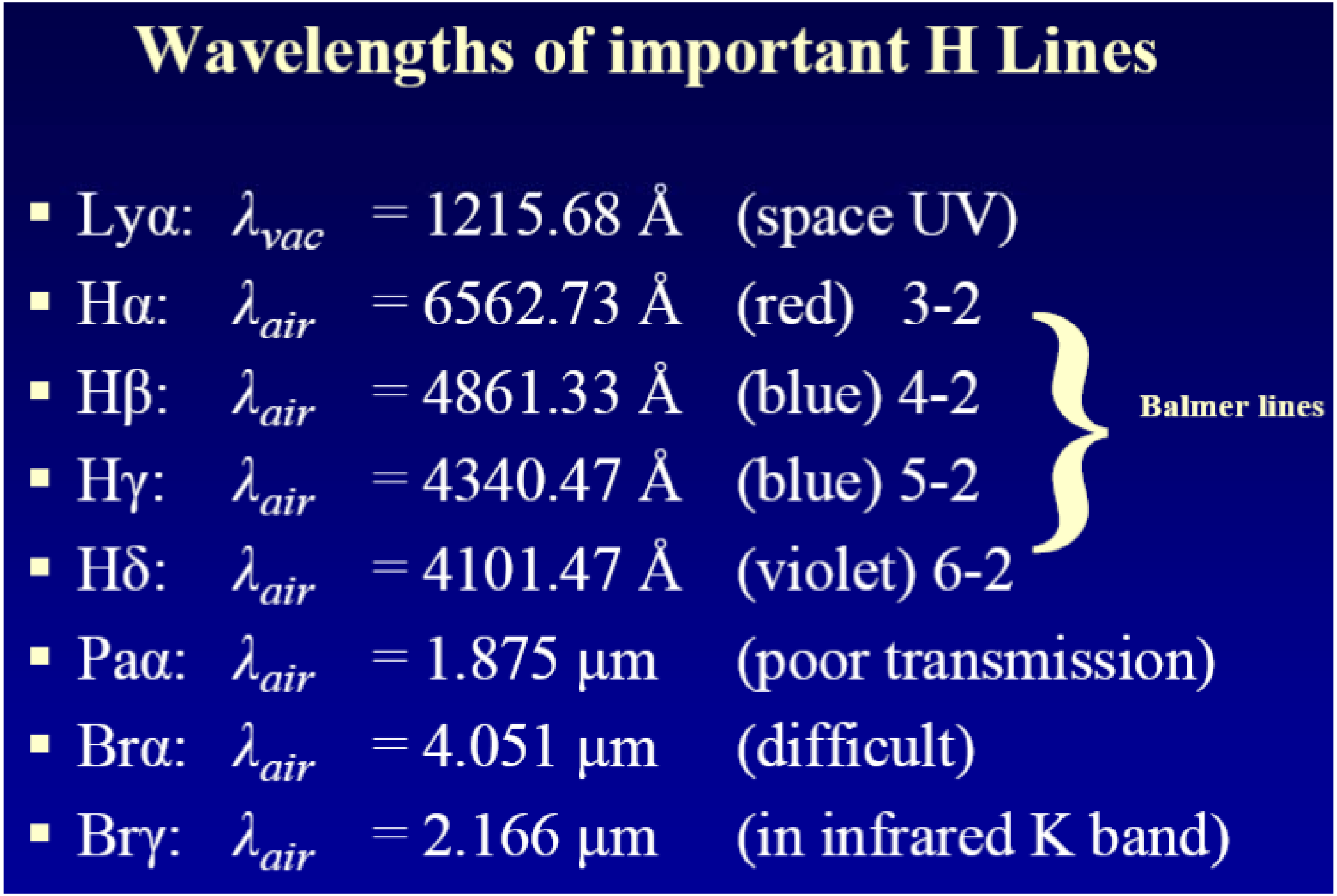
Balmer continuum

Free-free (bremsstrahlung)

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

Hydrogen spectrum --- permitted transitions



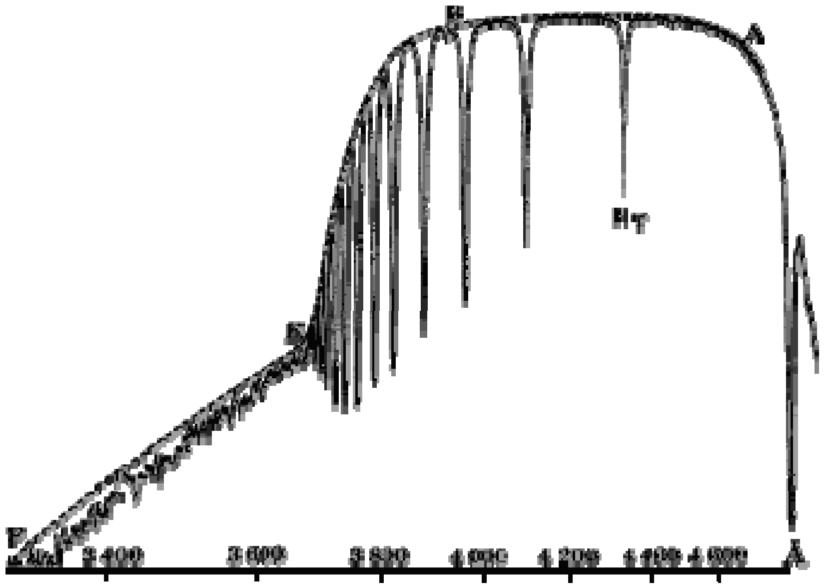


Wavelengths of important H Lines

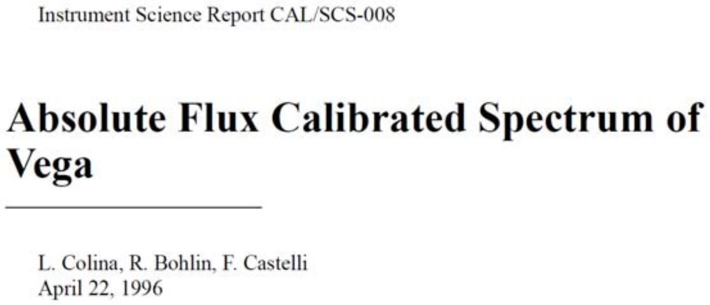
- Lyα: $\lambda_{vac} = 1215.68$ Å (space UV)
- Hα: $\lambda_{air} = 6562.73$ Å (red) 3-2
- Hβ: $\lambda_{air} = 4861.33$ Å (blue) 4-2
- Hγ: $\lambda_{air} = 4340.47$ Å (blue) 5-2
- Hδ: $\lambda_{air} = 4101.47$ Å (violet) 6-2
- Paα: $\lambda_{air} = 1.875$ µm (poor transmission)
- Brα: $\lambda_{air}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

Balmer lines

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



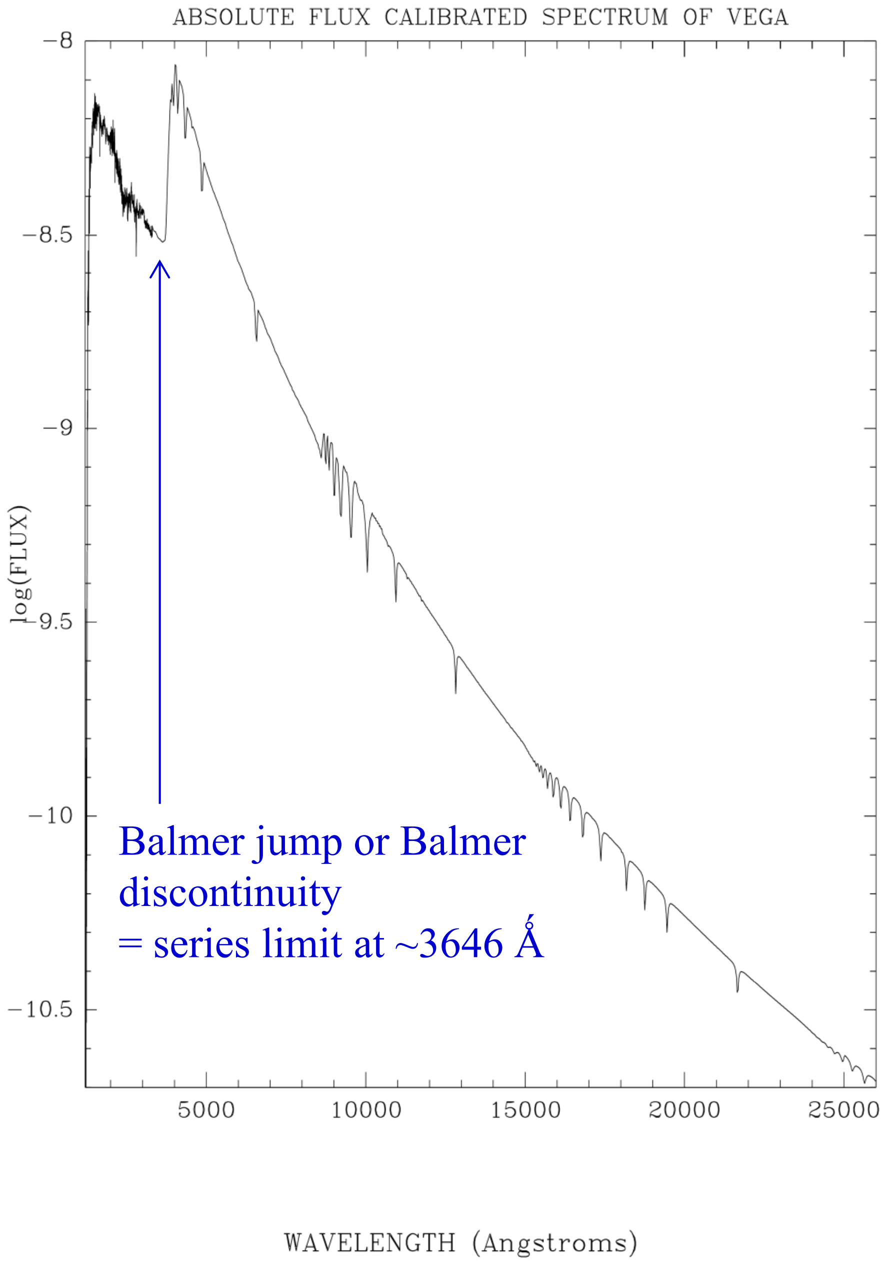
the spectra of the hot star alpha Lyra (Vega), observed by Barbier and Chalonge (1939)



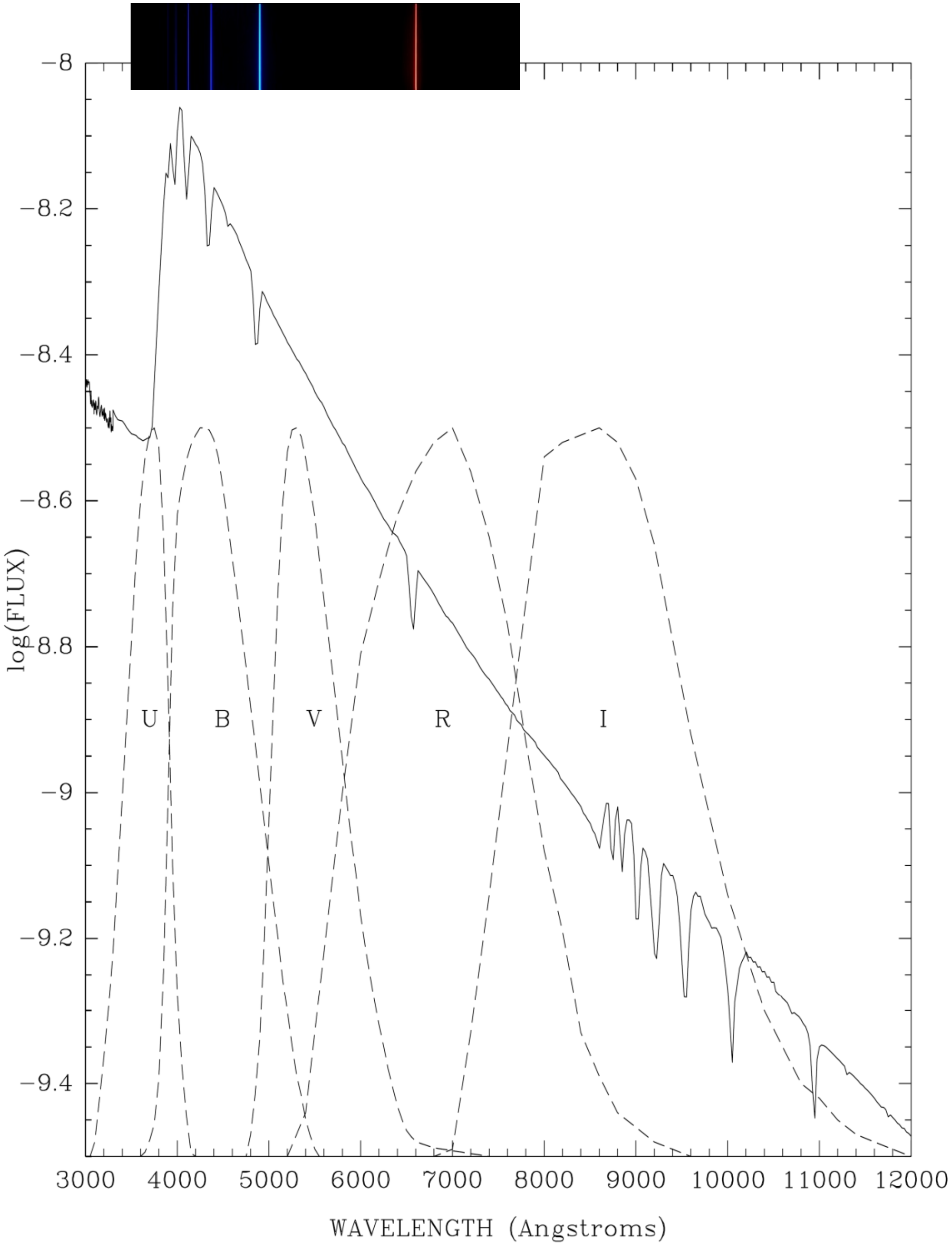
Instrument Science Report CAL/SCS-008

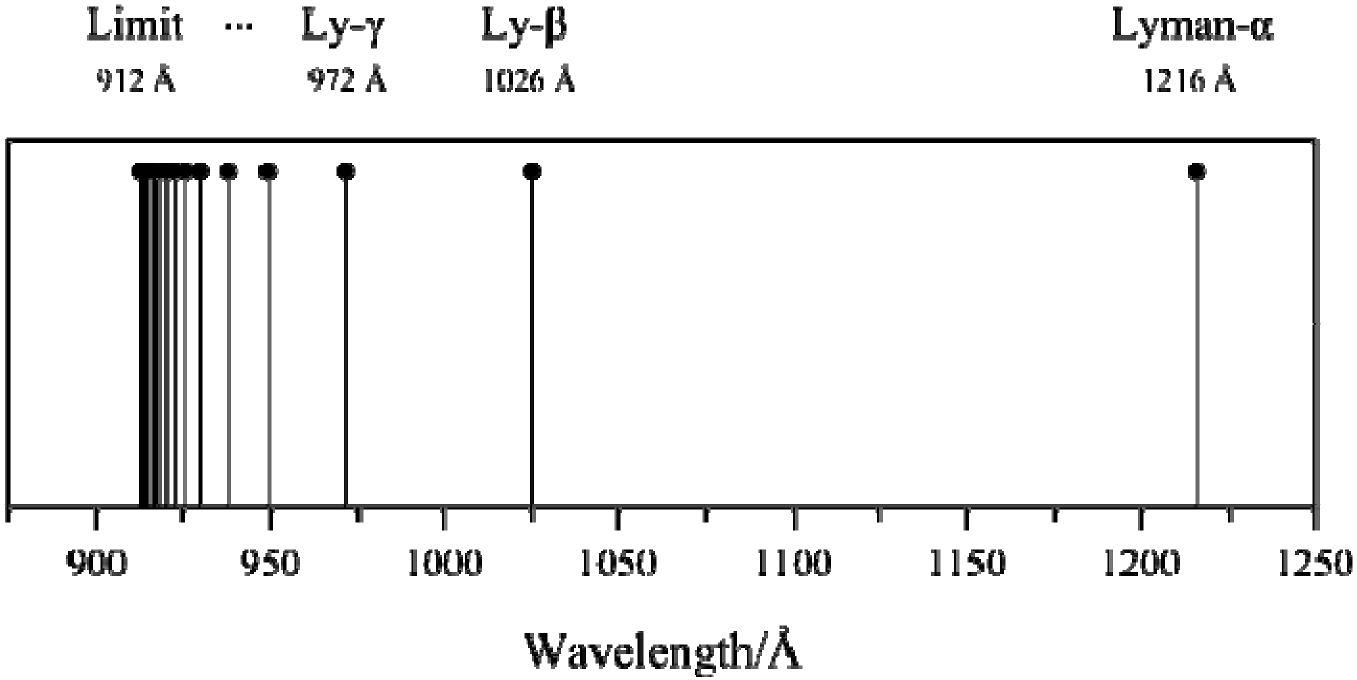
Absolute Flux Calibrated Spectrum of Vega

L. Colina, R. Bohlin, F. Castelli
April 22, 1996



Balmer jump or Balmer discontinuity
= series limit at ~3646 Ǻ


−8
−8.2
−8.4
−8.6
−8.8
−9
−9.2
−9.4
log(FLUX)
U
B
V
R
I
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
WAVELENGTH (Angstroms)



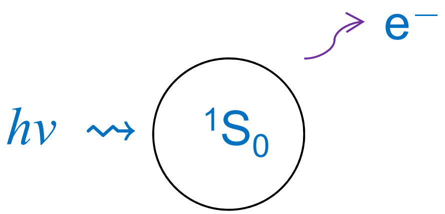
http://en.wikipedia.org/wiki/File:LymanSeries.svg

The transition probability between an upper level and a lower level is characterized by the Einstein A and B coefficients

- Absorption (0→1)
  - ➔ B_{01} or oscillator strength f10
- Emission (1→0)
  - ➔ A_{10}

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

Probability of **photoionization**
→ photoionization cross section



$\mathrm{H} + h\nu \rightarrow \mathrm{H}^+ + e$
$E_{\mathrm{kin}}(e) = h\nu - 13.6 \text{ eV}$

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

Gaunt factor (or Kramers-Gaunt factor) = correction when using classical physics for continuous absorption or emission …. differs from 1.0 if QM becomes important.

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

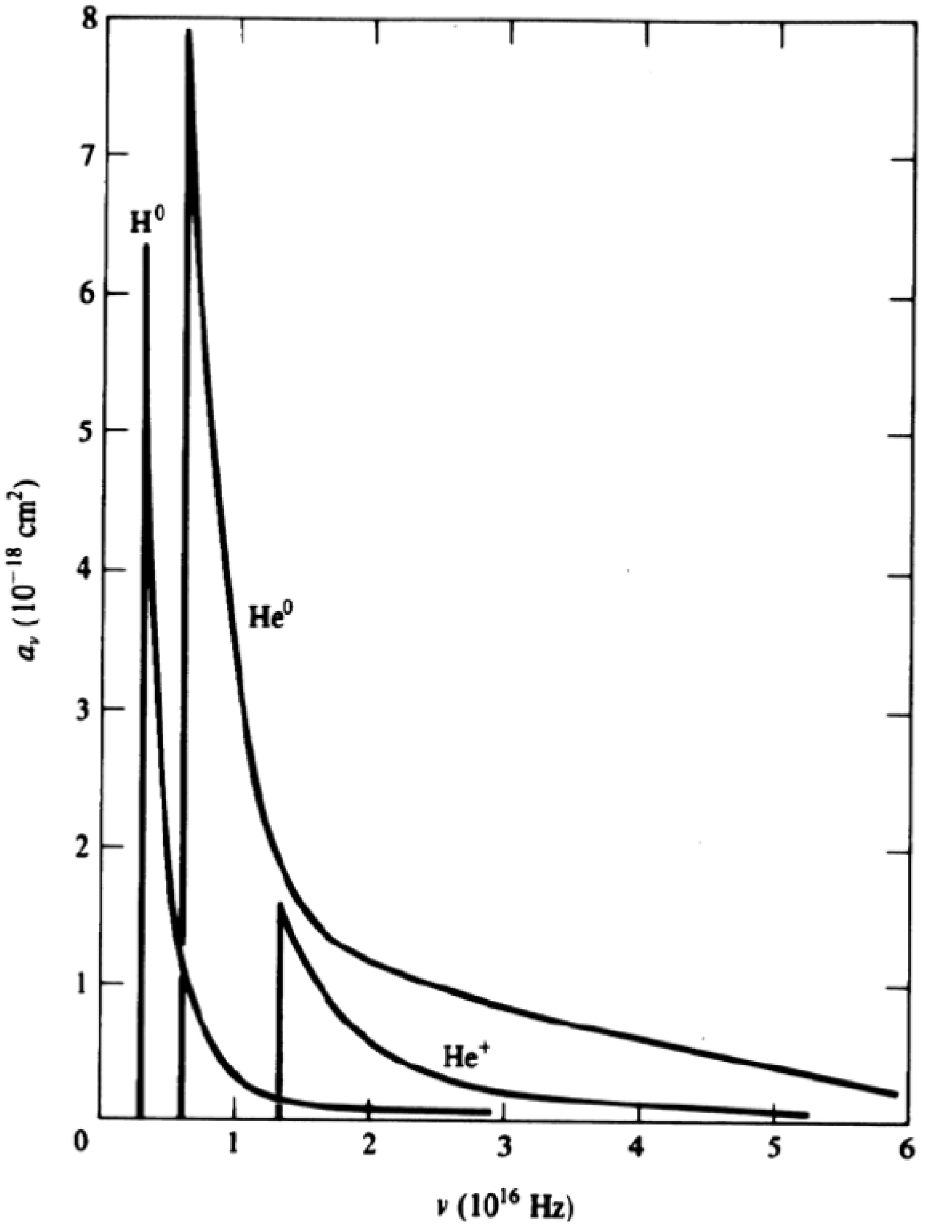
$$\boxed{\sigma_{\text{ion}}(\nu) \approx 6.3 \times 10^{-18} \, (\frac{\nu_1}{\nu})^3 [\text{cm}^2]}$$

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

[# of ionization] s^{-1} atom^{-1} due to photons in ν 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

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

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

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.

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

$\alpha^{(2)} = \sum_{n=2}^{\infty} \alpha_n = 4.54 \times 10^{-13}\ \mathrm{cm}^3{\cdot}\mathrm{s}^{-1}$ (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*

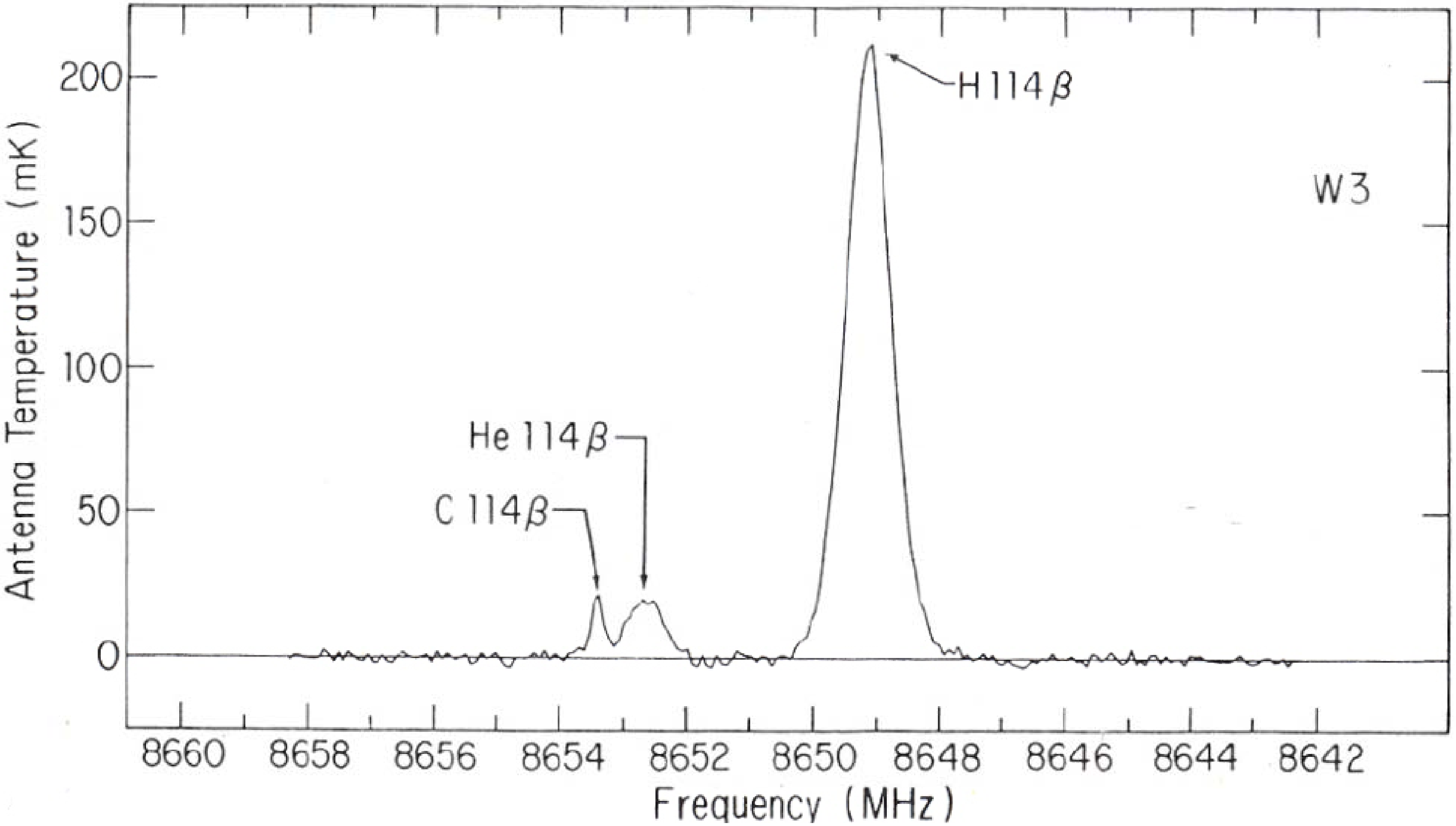
$\alpha_{n\ ^2L}$	T		
	5000° K	10,000° K	20,000° K
$\alpha_{1\ ^2S}$	2.28×10^{-13}	1.58×10^{-13}	1.08×10^{-13}
$\alpha_{2\ ^2S}$	3.37×10^{-14}	2.34×10^{-14}	1.60×10^{-14}
$\alpha_{2\ ^2P}$	8.33×10^{-14}	5.35×10^{-14}	3.24×10^{-14}
$\alpha_{3\ ^2S}$	1.13×10^{-14}	7.81×10^{-15}	5.29×10^{-15}
$\alpha_{3\ ^2P}$	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}.

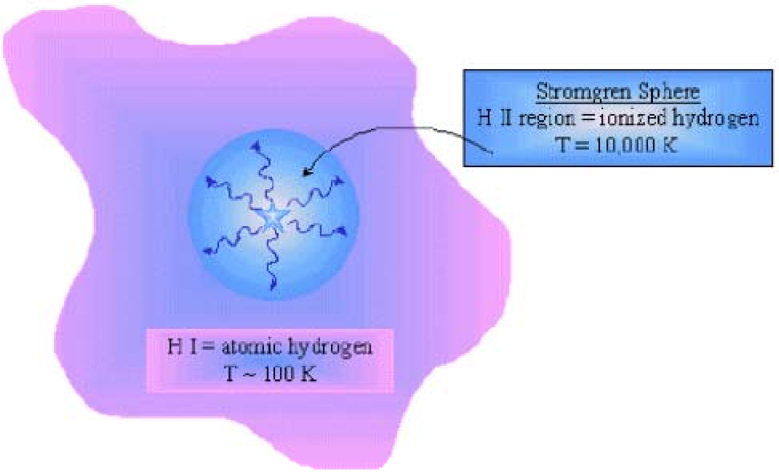
Recombination → photons

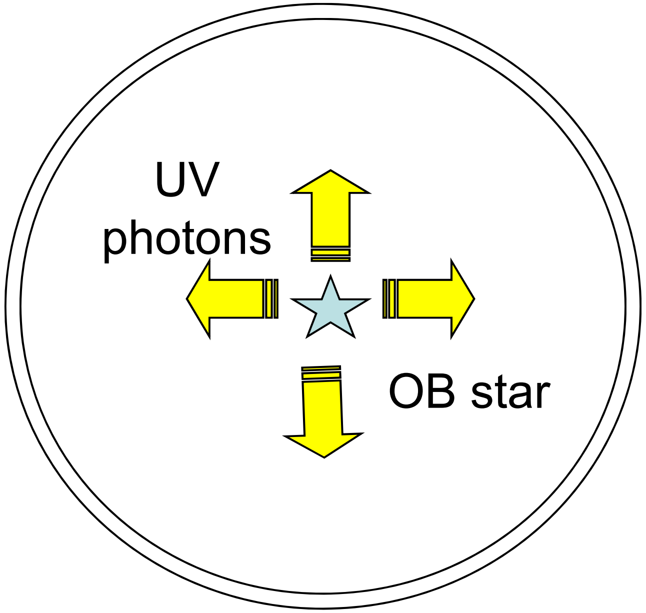
Some of the photons can ionize or excite other species

H 114 β: n=116 →114



Application: H II regions





Radiation λ< 912Å → ionization from gr state

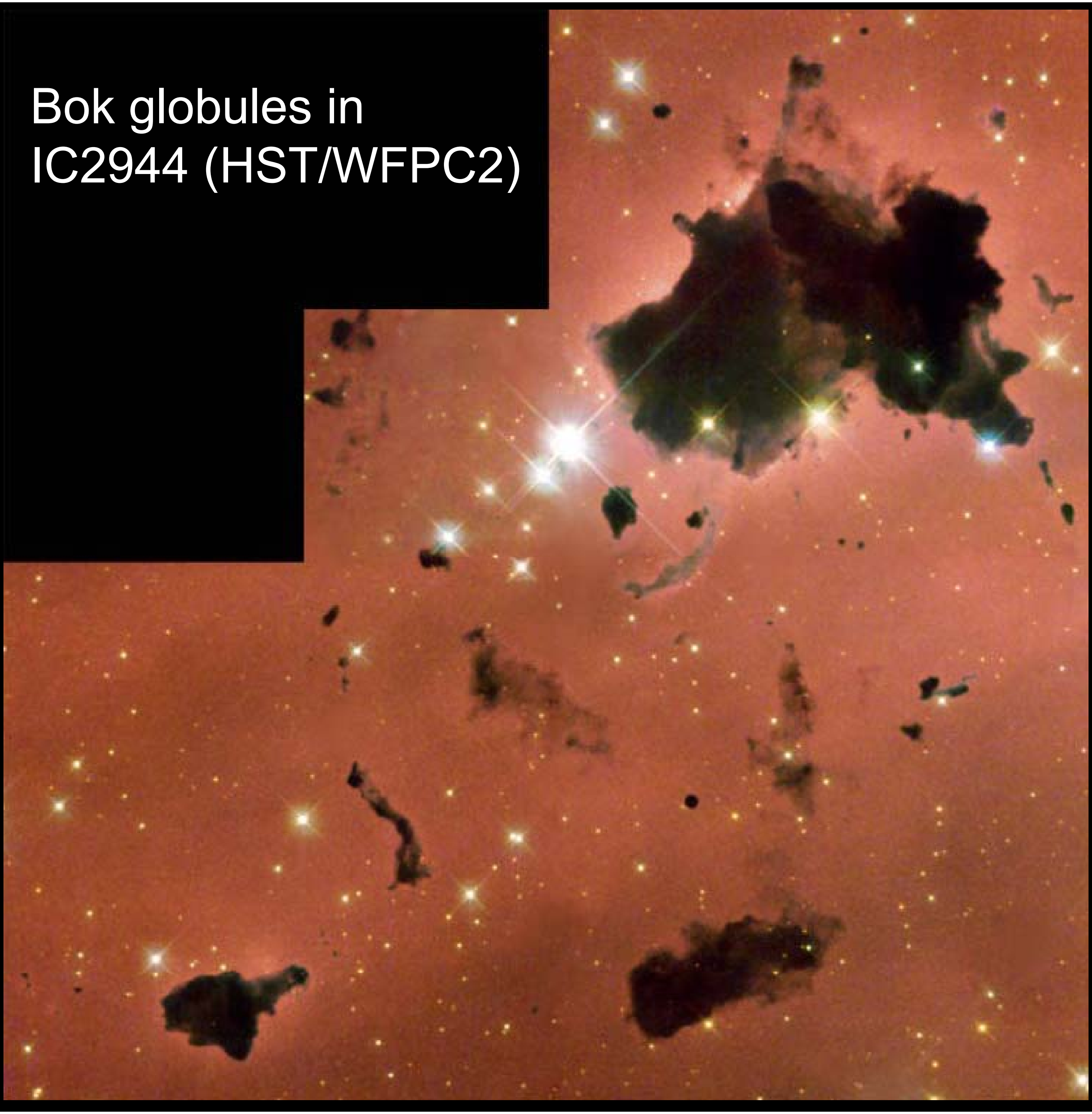
If e already in an excited state, a longer λ will do

Collisional ionization negligible in HII regions

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

→ e cascading → Hα

Bok globules in IC2944 (HST/WFPC2)



Strömgren Sphere

Strömgren (1939) ApJ, 89, 526
McCullough (2000) PASP, 112, 1542

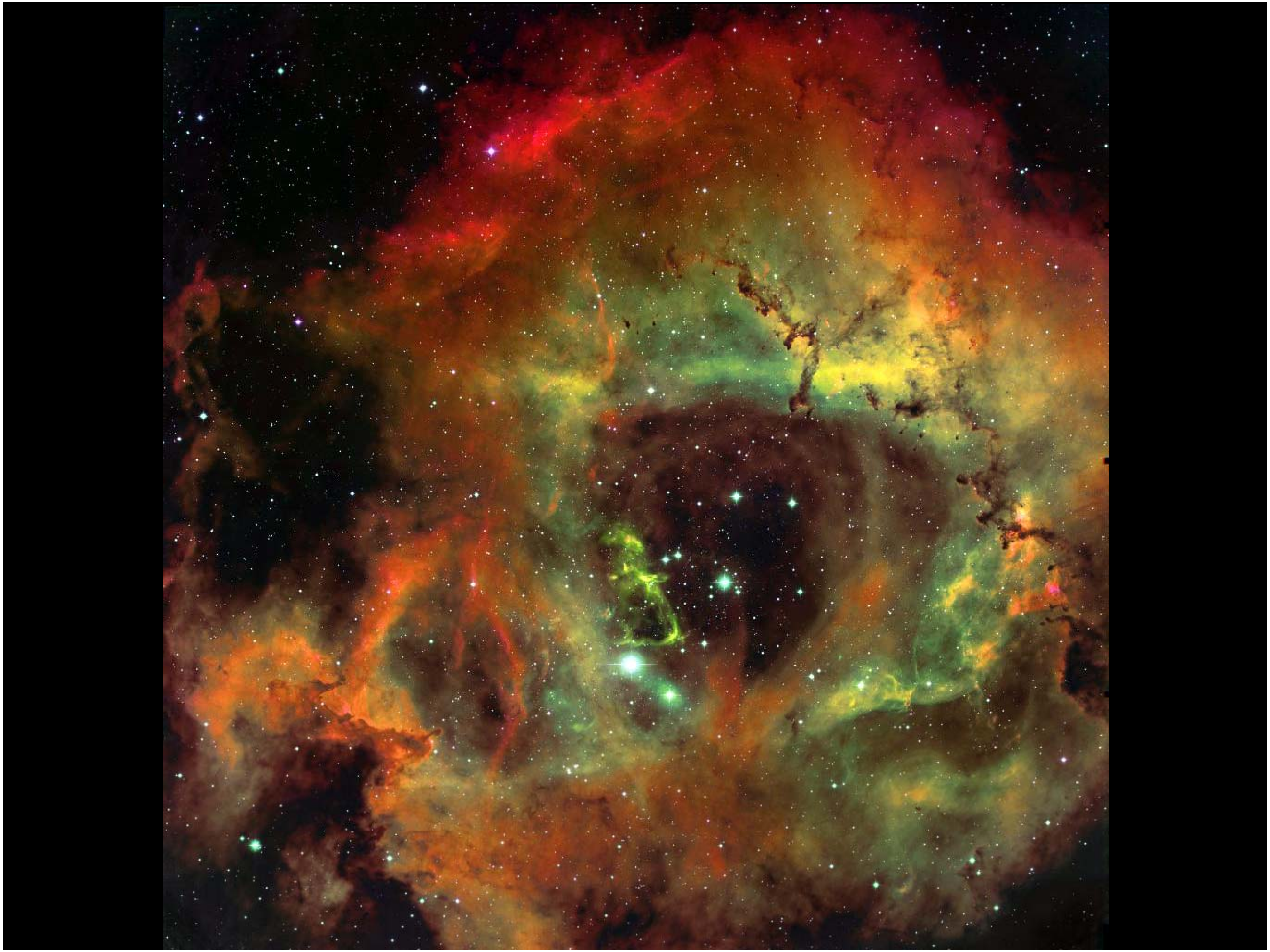
The Strömgren radius, R_s, within which
total # of recombinations to levels except the gr. state
= total # of ionizing photons from the luminous star

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}]

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



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

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

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

Strömgren radius

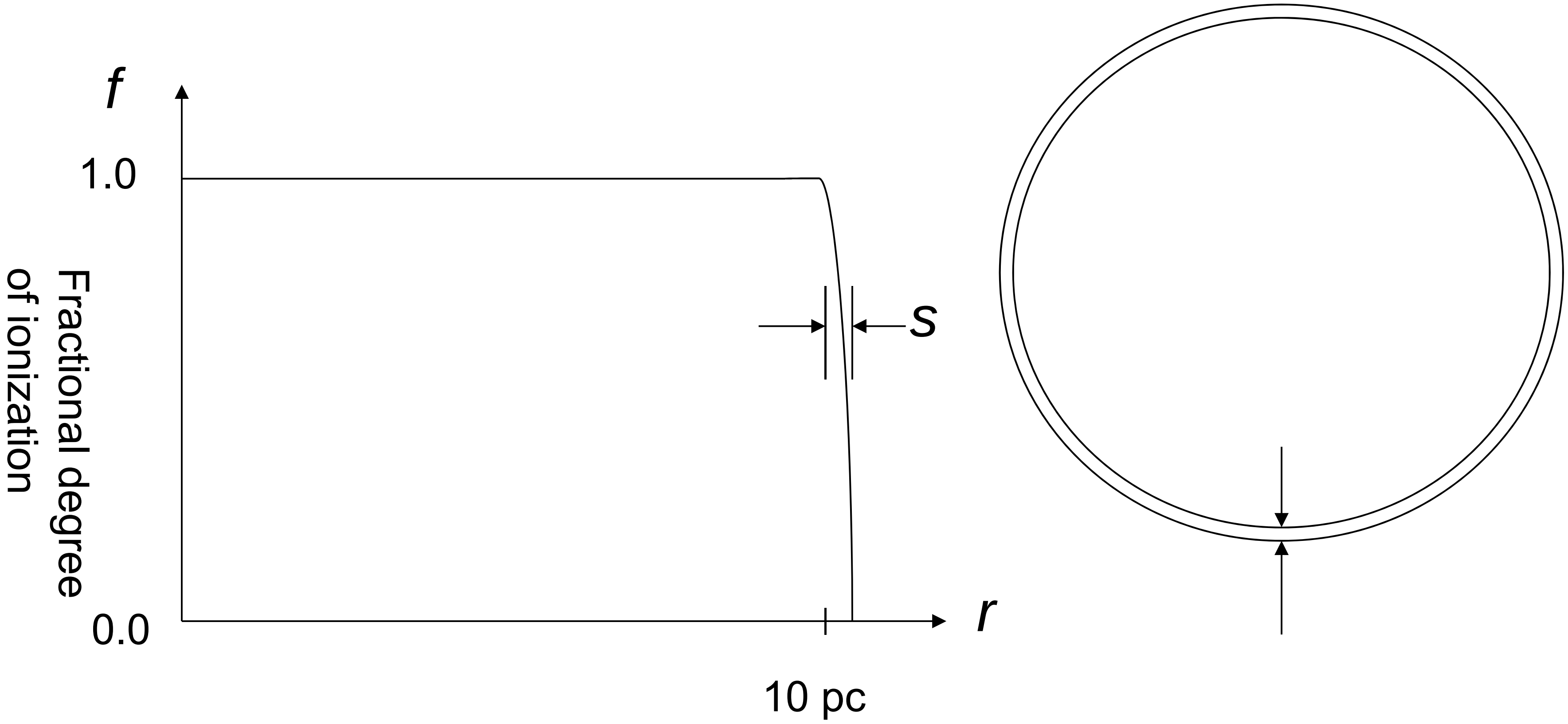
$$L^*_{912} \approx 5 \times 10^{42} \exp(3.2 \times 10^{-4}\ T_*)$$

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

Strömgren sphere = H II region = ionization cavity

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, $\underline{\tau} = \sigma_\nu^{\mathrm{ion}}\, n_H\, \underline{s \approx 1}$

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

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

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 $R_s \downarrow$ cf. http://tesla.phys.unm.edu/phy537/

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

- Helium can also be ionized, $\lambda < 506$ and < 208 Å
- Stars very hot, $T^* > 10^5$ K
- Ionization Application

  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_* is inferred --- **Zanstra Method**

Evolution of an H II region

- An H II region is formed around a very hot star.
- Original H I, T~100 K; now H II, $T \uparrow \uparrow$ (~10^4 K), ionization produces free electrons, so $n \uparrow$, hence pressure ↑ ↑ → H II region expands, v~ sound speed of the hot gas ~ 10 km/s
- Sound speed in H I ~ 1 km/s, the H II expansion is highly supersonic → a shock front
- H II continues to expand ($n \downarrow$) until pressure equilibrium with the H I region. This takes 10^7 to 10^8 years. But an early O star has a main-sequence lifetime of 10^6 years
  ➔ all H II regions are expanding!

Strings of red H II “knots” delineate the arms of the Whirlpool Galaxy = sites of recent star formation

- If there is plenty of dust, the radiation pressure would push the grains outwards → changes the density structure → an expanding dust front (and drag the gas along); the dust shell is optically thick in the optical so the central star and developing H II region = an IR source embedded in an H I region.
- Dust also absorbs some stellar Lyman photons → ionization rate ↓, and Strömgren radius ↓
- For really hot stars, O6.1 V and earlier, O5.3 III and earlier, or O4 I and earlier, He is also ionized inside the Strömgren sphere.

$E_{\mathrm{He,\ ion}} = 24.6\ \mathrm{eV}$

- H II regions have moving charges → electric field and magnetic field
- Each H II region may contain many OB stars.
- Young H II regions = compact H II regions

  Newly formed H II regions = ultra-compact H II (UCHII) regions (D < 0.3 pc); hyper-compact H II regions ➔ study of massive star formation
- H II regions are bright (seen at large distances) and the sizes of the largest H II regions in galaxies should be roughly the same → distance yardstick for distant galaxies