Ionization Processes

- Photoionization
- Auger ionization
  once photoionized of an inner-shell electron
  → a 2-electron transition, one to fill the vacancy, the other one excited or ionized
- Collisional ionization
- Cosmic Ray Ionization

Ionization fraction $x_e \equiv n_e/n_H$

- In a dense molecular cloud, $x_e \lesssim 10^{-6}$
- In HI gas, C photoionized by starlight, H partially ionized by cosmic rays;
  $10^{-3} \lesssim x_e \lesssim 10^{-1}$, depending on density, temperature, and CR energetics
- In an H II region, H almost entirely photoionized, He mostly singly ionized, O and Ne doubly ionized (O III and Ne III)
- In a supernova remnant, elements up to C fully ionized; C or Ne innermost e^- in 1 s shell
- In an IGM "Lyman α cloud with $N(H\ I) \lesssim 10^{17}$ cm^{-2}, H and He mostly ionized (H II, He III), C triply ionized (C IV)

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

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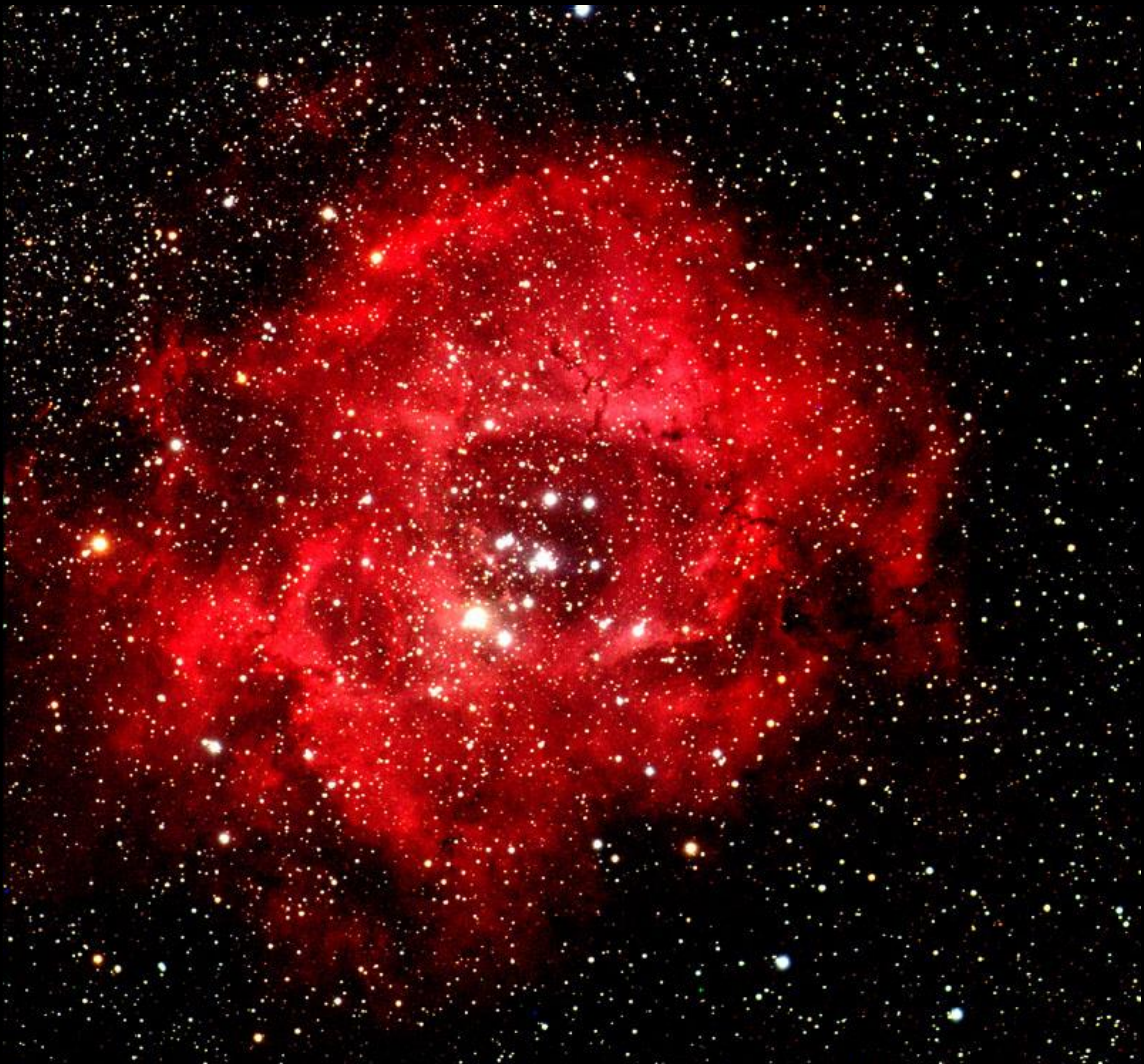
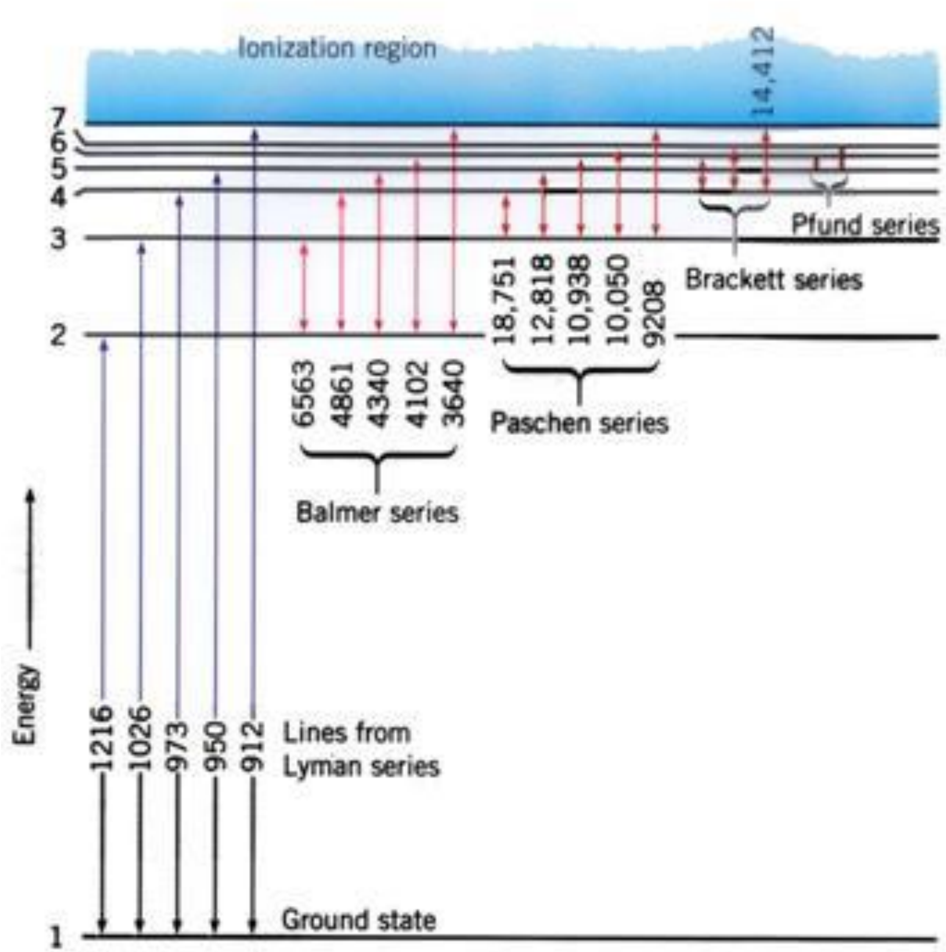
(iii) **Forbidden lines**



Photoionization

Lyman continuum

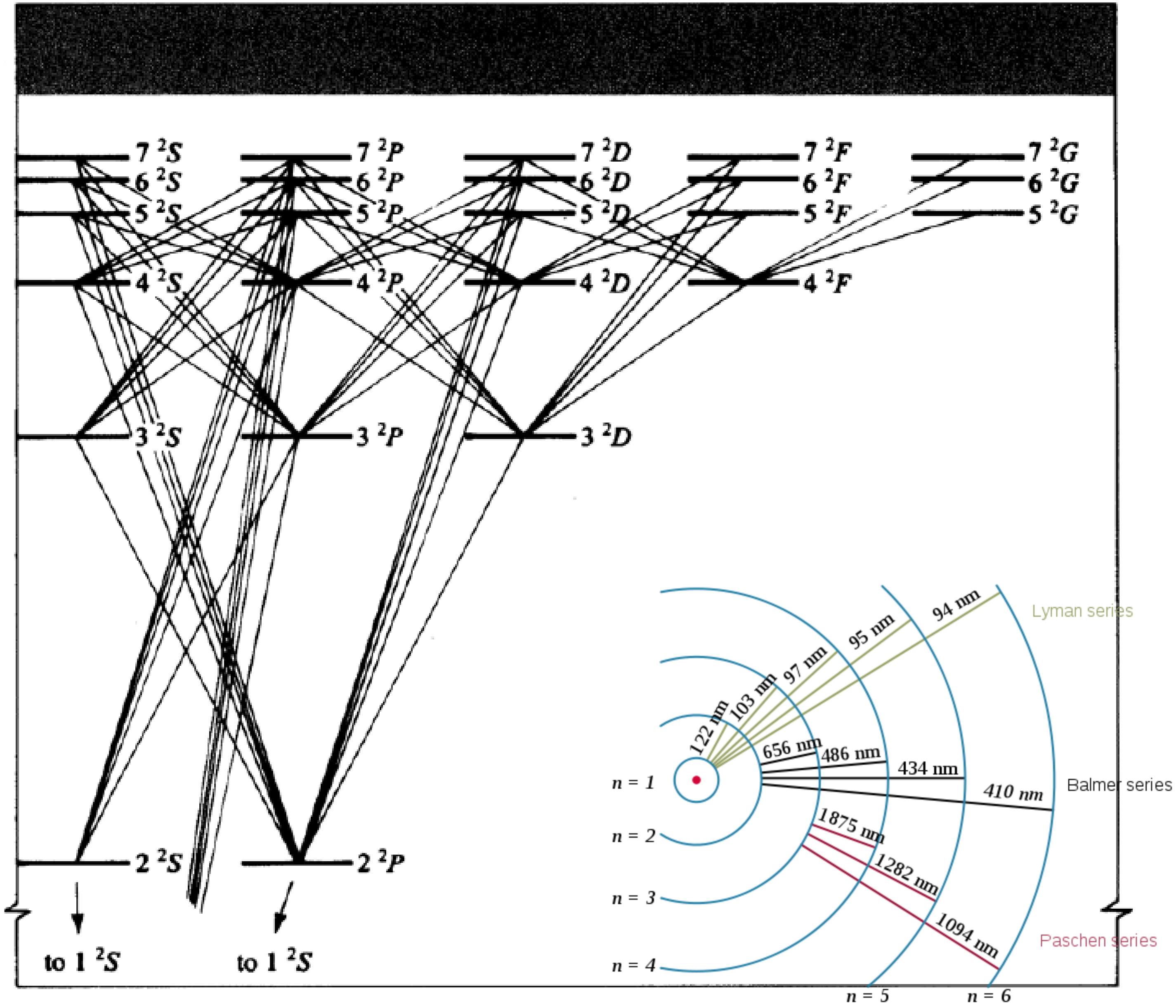


Balmer continuum

Free-free (bremsstrahlung)

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

Hydrogen spectrum --- permitted transitions

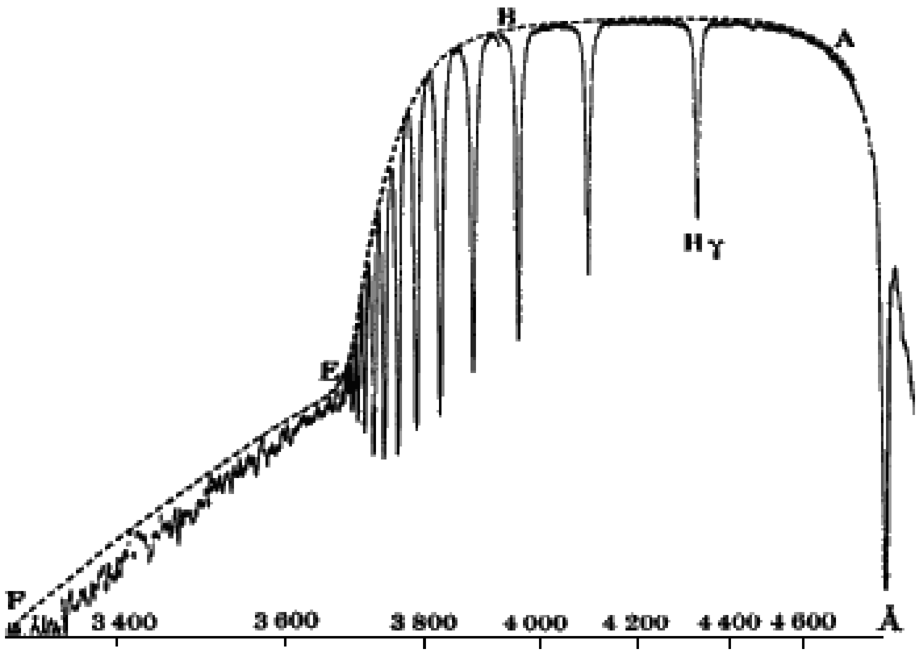


Wavelengths of important H Lines

- Lyα: 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

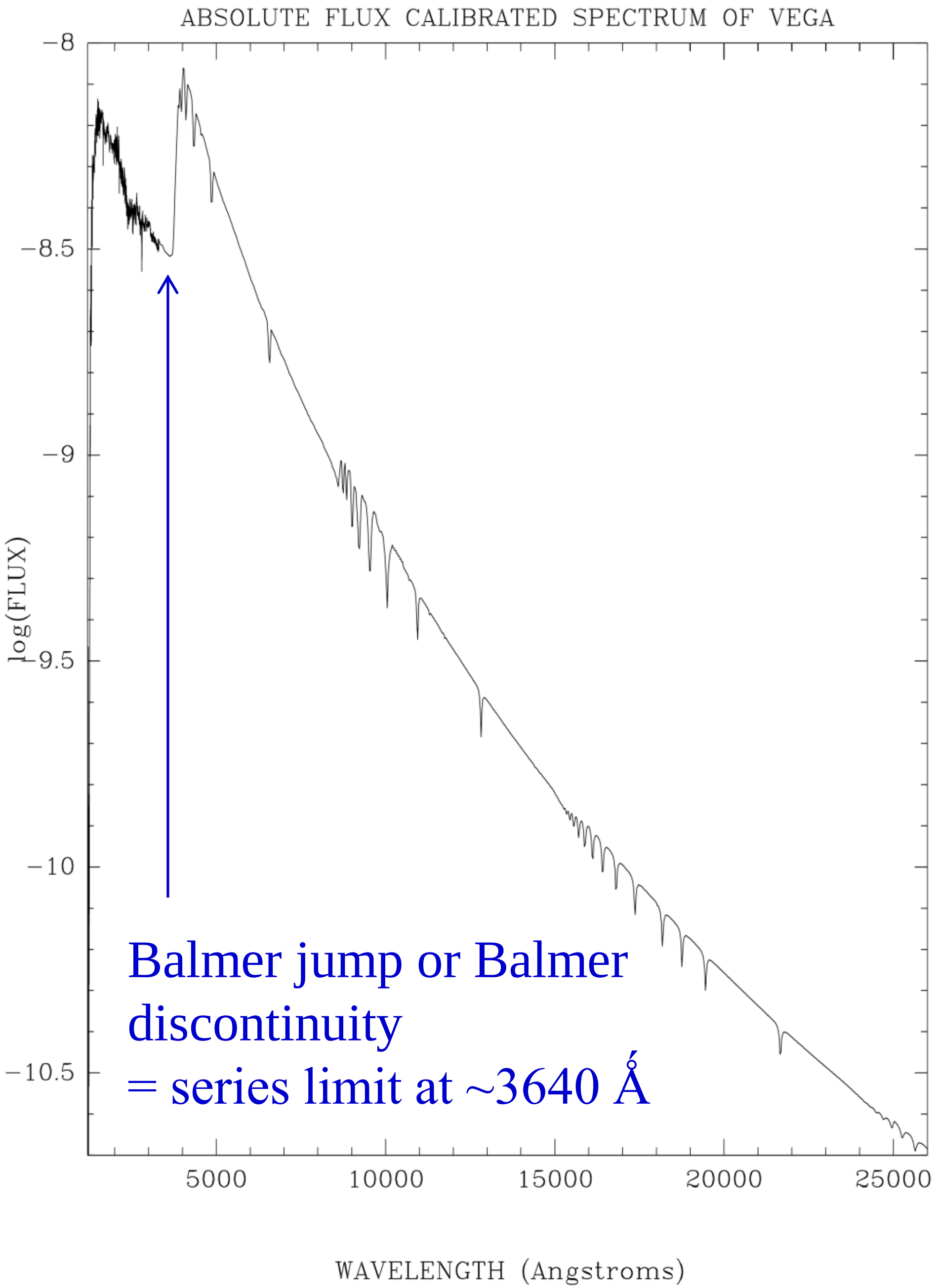


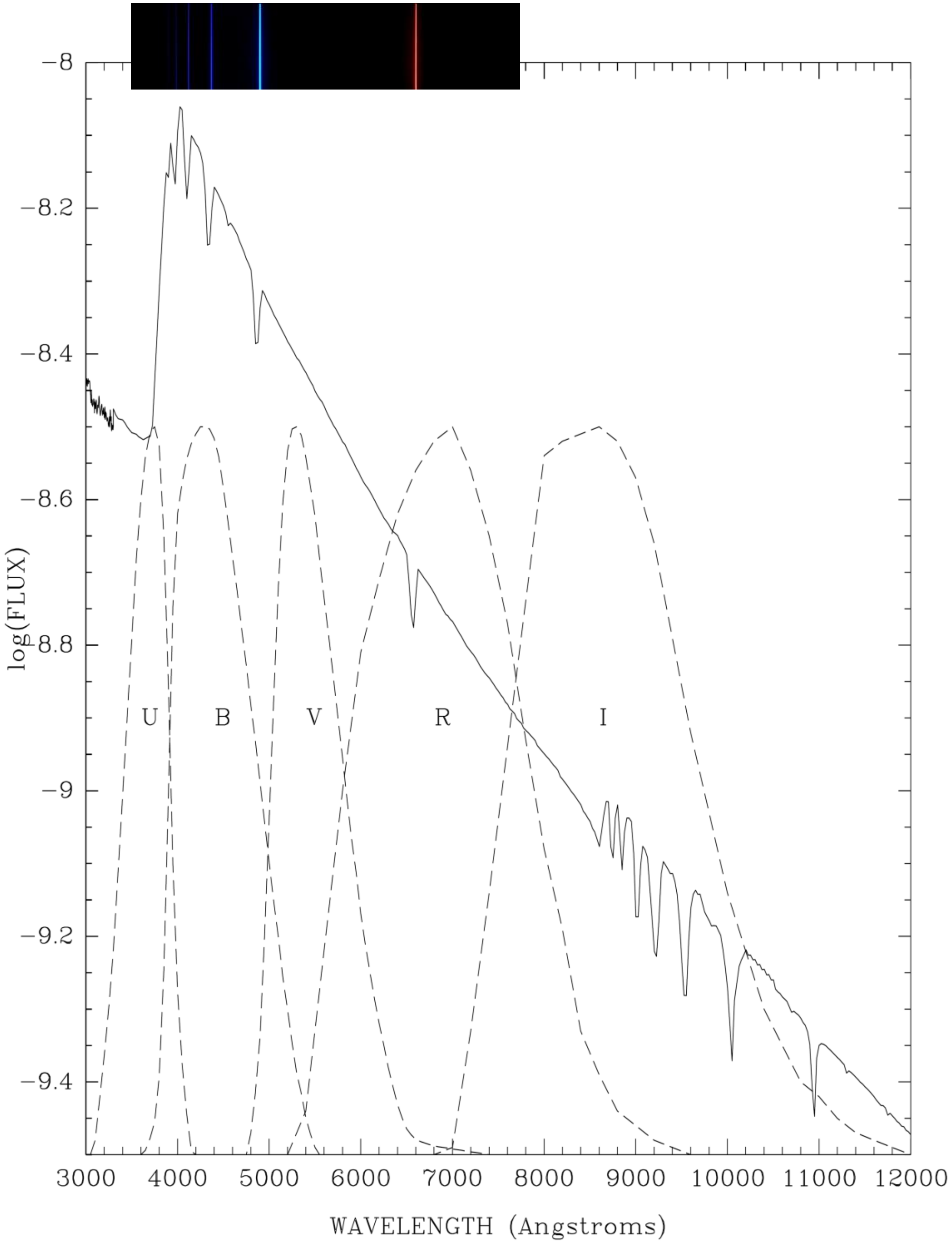
the spectra of the hot star alpha Lyra (Vega), observed by Barbier & Chalonge (1939)

Instrument Science Report CAL/SCS-008

Absolute Flux Calibrated Spectrum of Vega

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

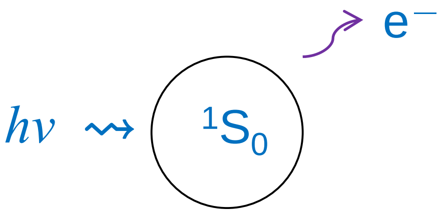



−8
−8.2
−8.4
−8.6
−8.8
−9
−9.2
−9.4
log(FLUX)
U
B
V
R
I
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
WAVELENGTH (Angstroms)

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 f_{10}
- Emission (1→0)
  ➔ A_{10}

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



Probability of **photoionization**
→ photoionization cross section

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

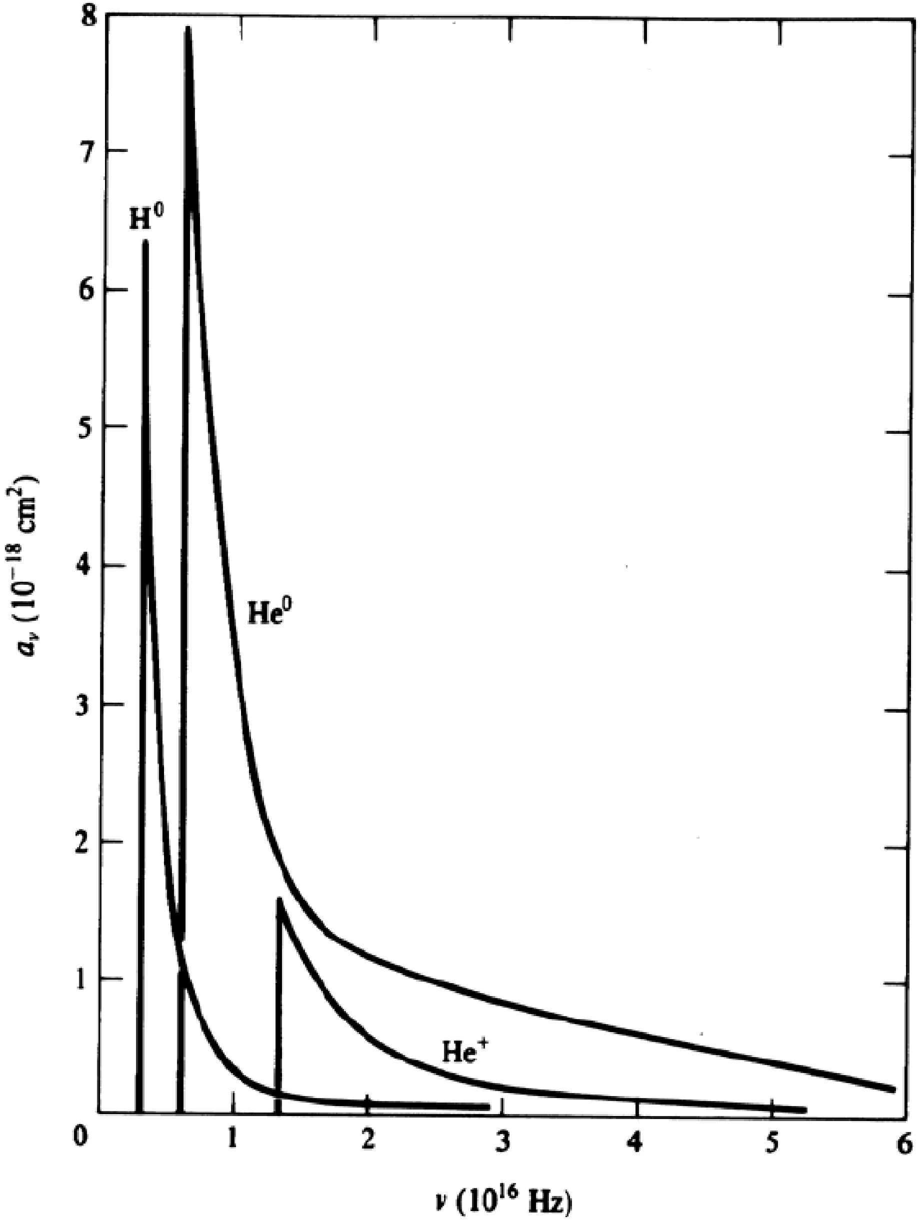
For H-like (hydrogenic) atoms, the photoelectric cross section is known analytically

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

where g_{1f} is Gaunt factor ≈ 1 at optical wavelengths,
$h\nu_1 = Z^2 h\nu_0 = 13.6\, Z^2\ \mathrm{eV}$

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

Photoionization cross sections for H, He and He^+



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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.

$\sigma_{\text{photoelectric}} \approx \sigma_{\text{Compton scattering}}$ for $h\nu \approx 2.5$ keV

[# of ionization] $\text{s}^{-1}\text{atom}^{-1}$ due to photons in ν to $\nu + d\nu = \sigma_\nu \frac{4\pi \langle I_\nu \rangle \, d\nu}{h\nu}$

Define the coefficient α, so that

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

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

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

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 $cm^3\ sec^{-1}$.

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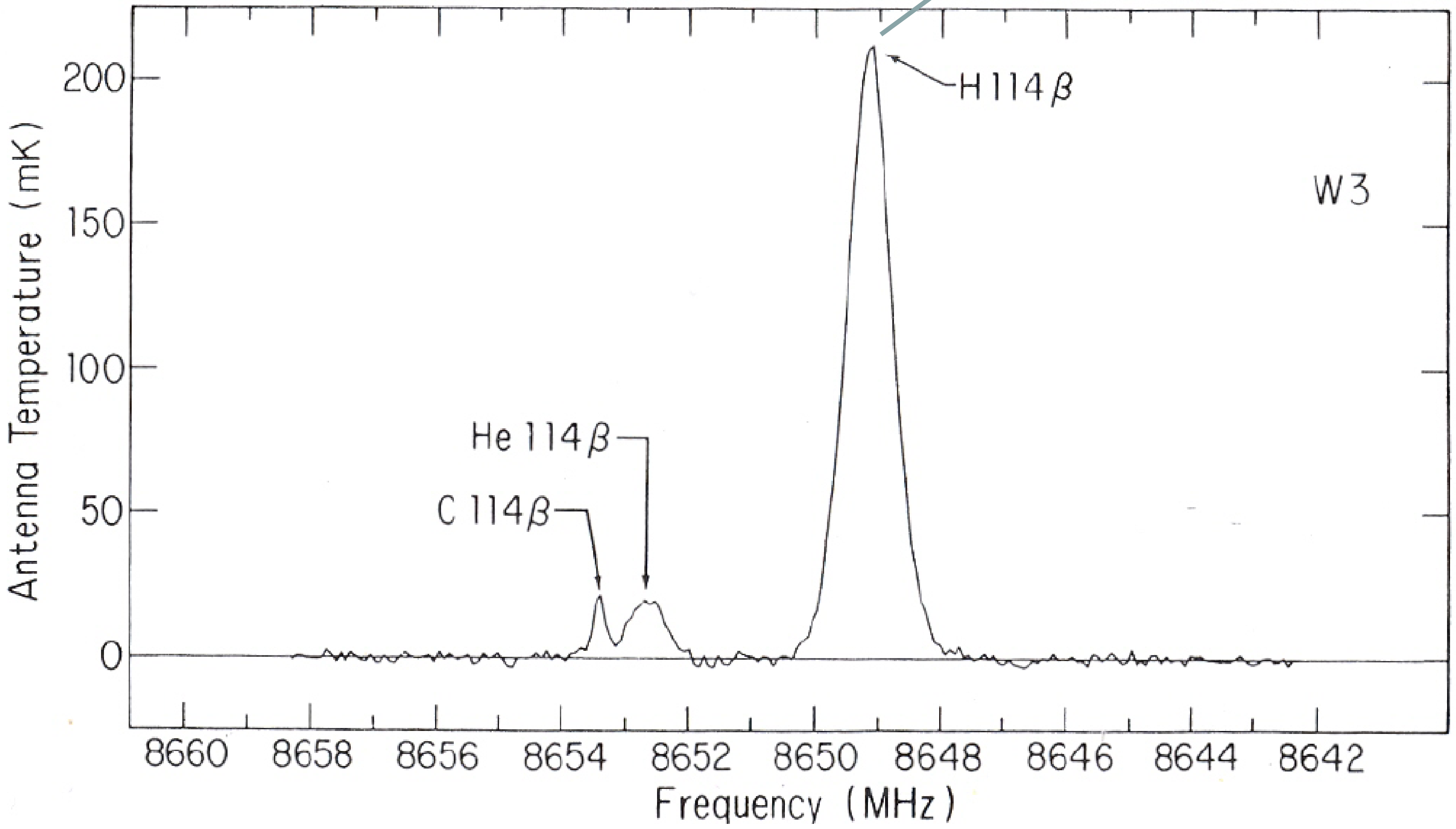
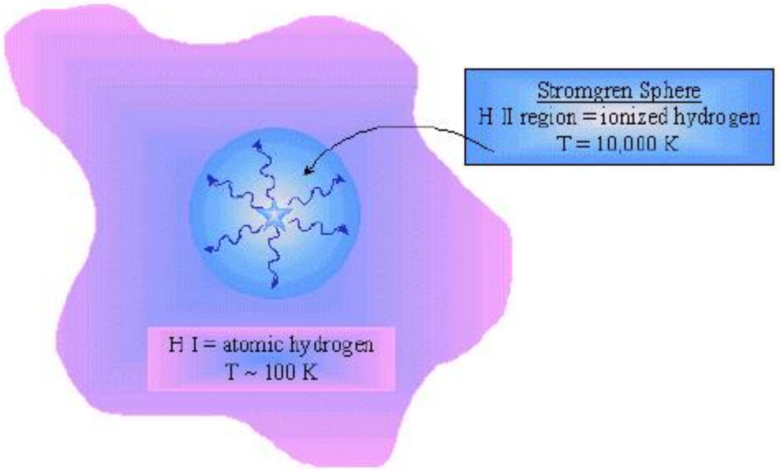
Recombination → photons

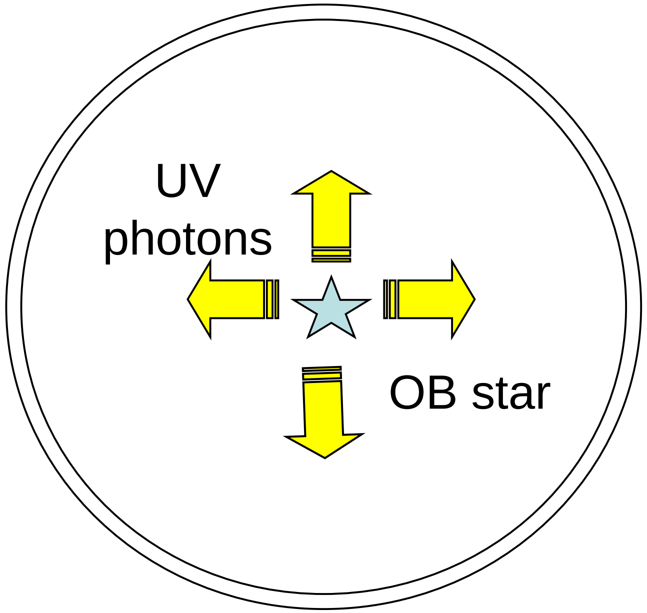
Some of the photons can ionize or excite other species

H 114 β: $n = 116 \rightarrow 114$



H II regions





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

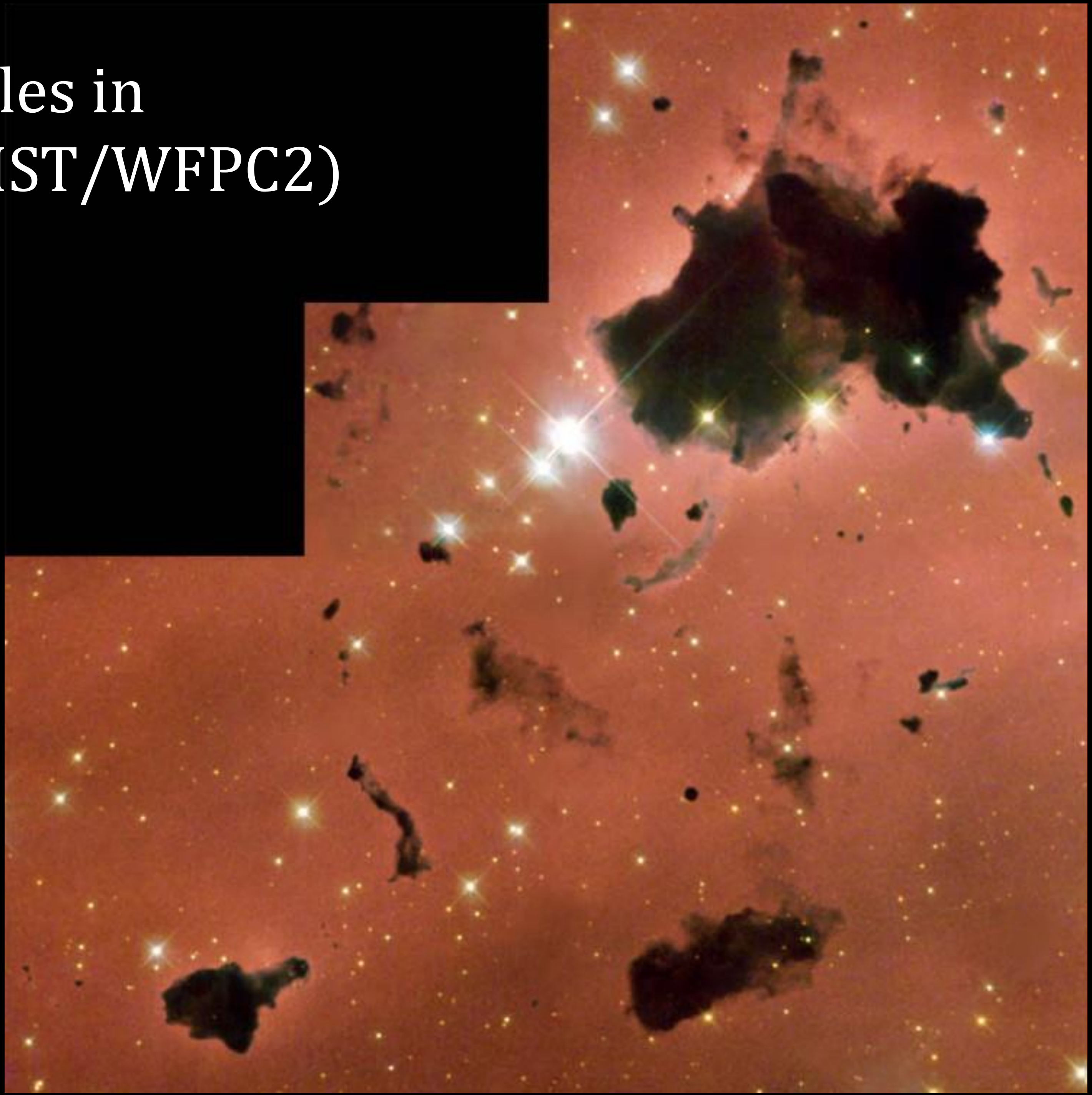
If *e* already in an excited state, a longer λ will do

Collisional ionization negligible in HII regions

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

e cascading → 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: $\alpha^{(2)} n_e n_p \, (4\pi R_s^3/3)$ **Case B**

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}]

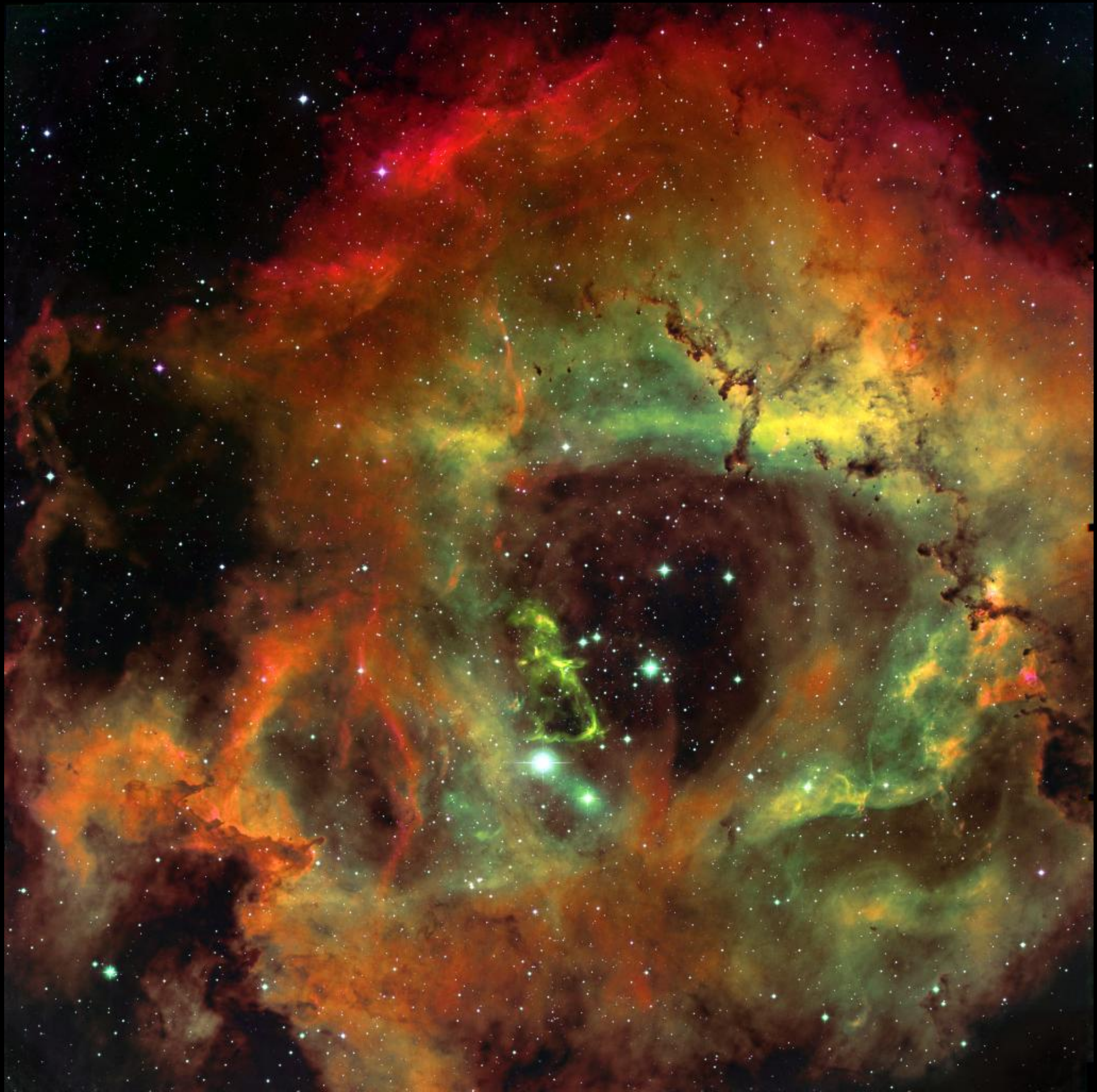
$$4\pi R_*^2 \int_{\lambda=912}^{\infty} \frac{\pi B_\nu(R_*)}{h\nu} \, d\nu = \alpha^{(2)} n_e n_p (4\pi R_s^3/3)$$

THE PHYSICAL STATE OF INTERSTELLAR HYDROGEN

BENGT STRÖMGREN

ABSTRACT

The discovery, by Struve and Elvey, of extended areas in the Milky Way in which the Balmer lines are observed in emission suggests that hydrogen exists, in the ionized state, in large regions of space. The problem of the ionization and excitation of hydrogen is first considered in a general way. An attempt is then made to arrive at a picture of the actual physical state of interstellar hydrogen. It is found that the Balmer-line emission should be limited to certain rather sharply bounded regions in space surrounding O-type stars or clusters of O-type stars. Such regions may have diameters of about 200 parsecs, which is in general agreement with the observations. Certain aspects of the problem of the ionization of other elements and of the problem of the relative abundance of the elements in interstellar space are briefly discussed. The interstellar density of hydrogen is of the order of $N = 3\ \mathrm{cm}^{-3}$. The extent of the emission regions at right angles to the galactic plane is discussed and is found to be small.



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

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

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

Strömgren radius

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

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

Strömgren sphere = H II region = ionization cavity

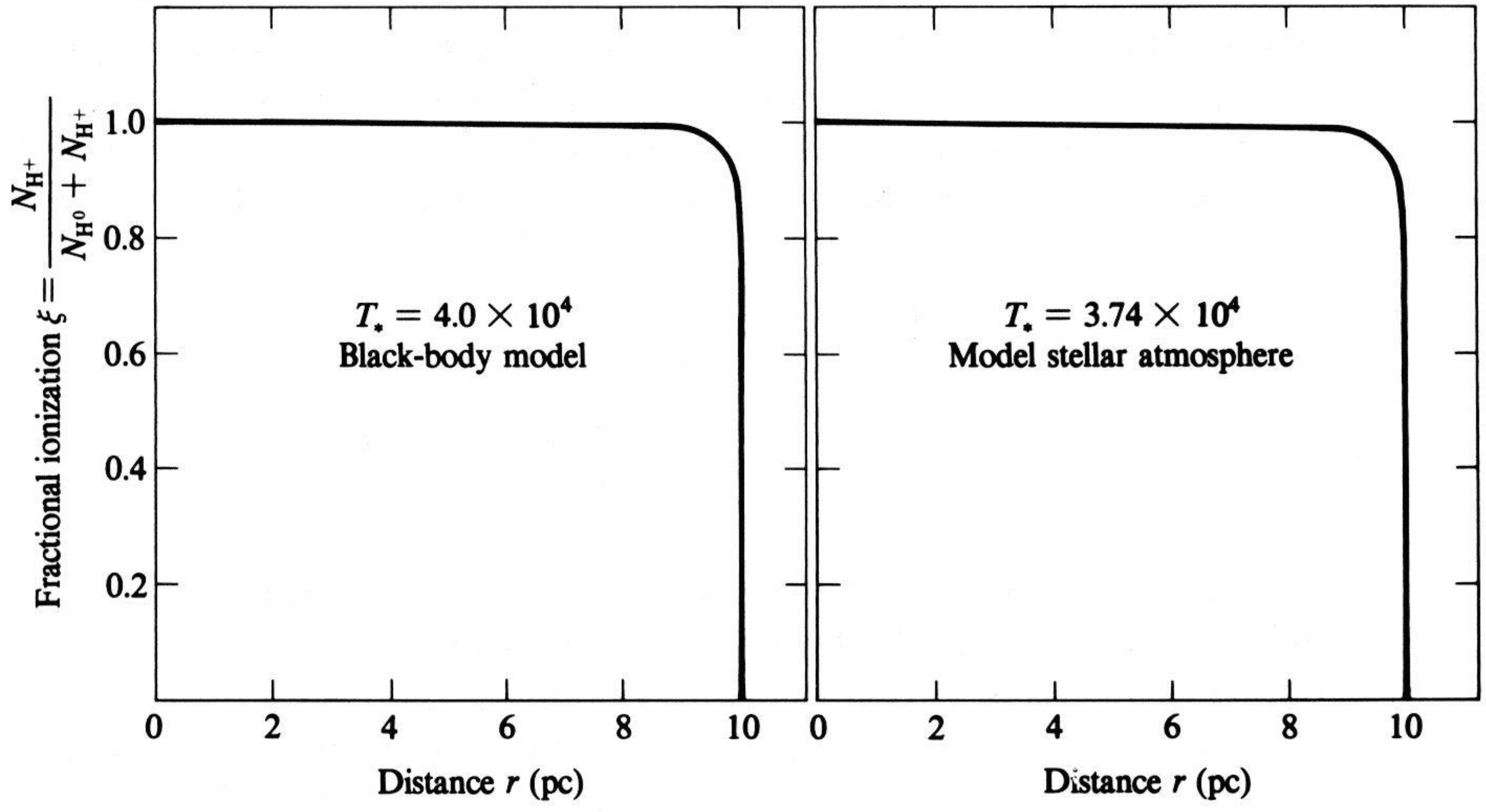


FIGURE 2.3
Ionization structure of two homogeneous pure-H model H II regions.

Osterbrock

Calculated radii of Strömgren spheres

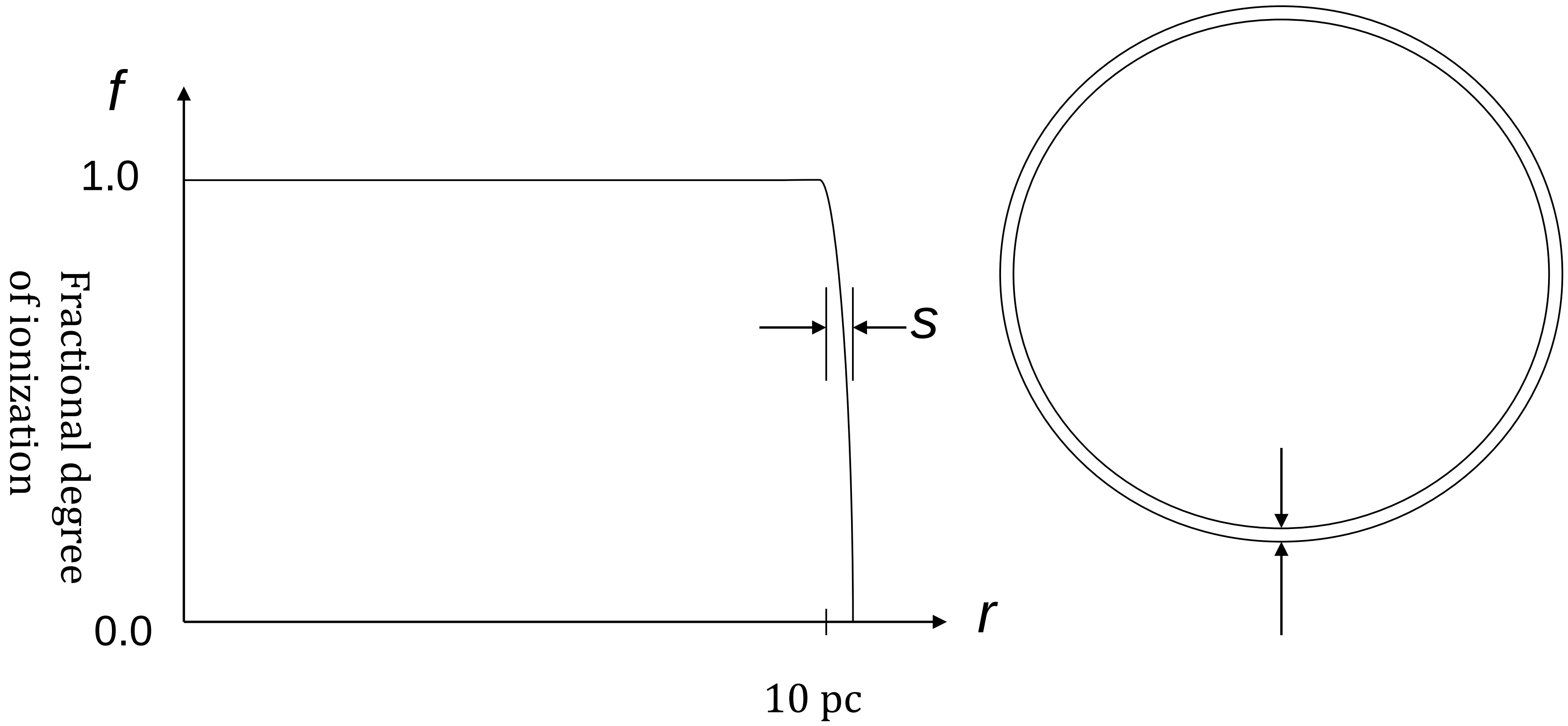
Spectral type	M_v	$T_*(°K)$	Log $Q(H^0)$ (photons/sec)	Log $N_e N_p r_1^3$ (N in cm^{-3}; r_1 in pc)	r_1 (pc) ($N_e = N_p$ = 1 cm^{-3})
O5	– 5.6	48,000	49.67	6.07	108
O6	– 5.5	40,000	49.23	5.63	74
O7	– 5.4	35,000	48.84	5.24	56
O8	– 5.2	33,500	48.60	5.00	51
O9	– 4.8	32,000	48.24	4.64	34
O9.5	– 4.6	31,000	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: $T = 7500°$ K assumed for calculating α_B.

Osterbrock

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

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

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]	$R_s\left(n_e n_p\right)^{1/3}$ [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

- He can also be ionized, λ< 506 Å and < 208 Å
- Stars very hot, T* > 10^5 K
- If all λ< 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 λ < 912 Å photons
  → all energy radiated by the star
  → T_* is inferred --- **Zanstra Method**

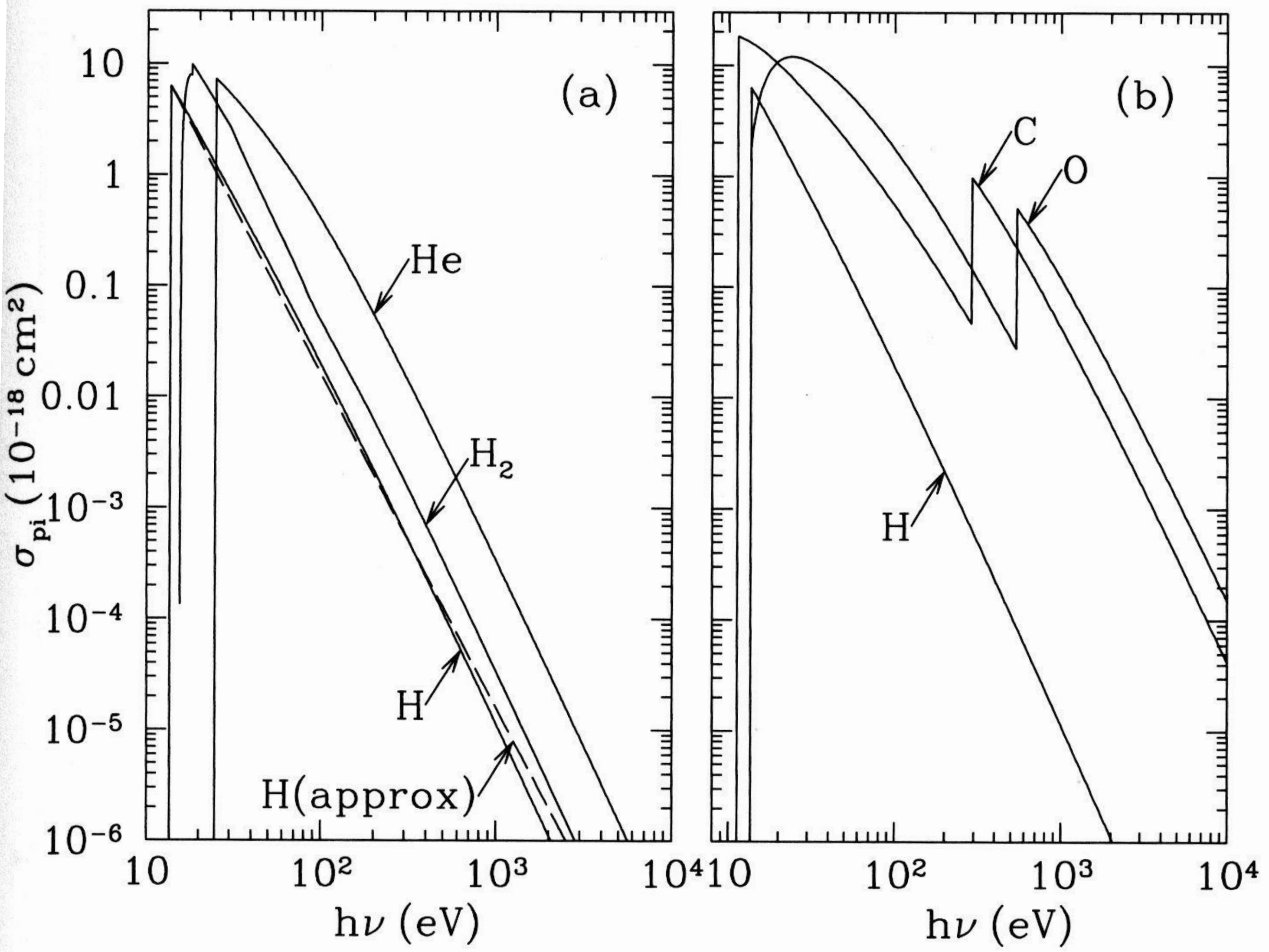


Figure 13.1 Photoionization cross sections for H, H_2, He, C, and O. The dashed line in (a) shows the power-law approximation (13.3) for H.

Draine

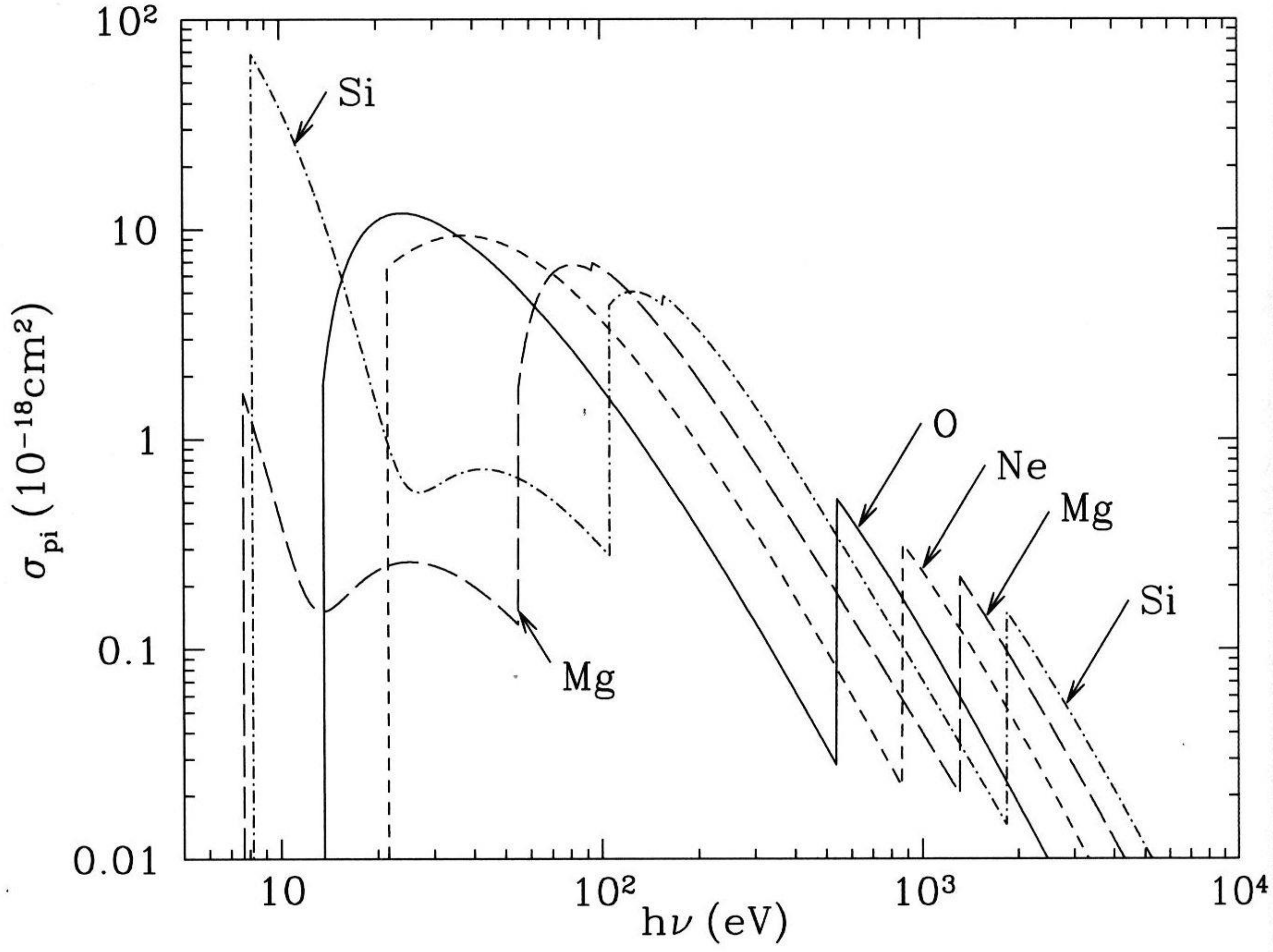


Figure 13.2 Photoionization cross sections for O, Ne, Mg, Si.

Draine

Evolution of an H II region

- An H II region is formed around a very hot star.
- Original H I, $T \sim 100$ K; now H II, $T\uparrow\uparrow$ ($\sim 10^4$ K), ionization produces free electrons, so $n\uparrow$, hence pressure $\uparrow\uparrow$ → H II region expands, $v\sim$ sound speed of the hot gas ~ 10 km/s
- Sound speed in H I ~ 1 km/s, so 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.

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

- H II regions have moving charges → **E** field and **B** 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 (say, 200 pc for several exciting stars), so angular sizes
  → distance yardsticks for distant galaxies

Planetary Nebulae

PNe ≈ H II regions, i.e., with ionized gas surrounding very hot stars, except for a PN

- Surrounding gas = wind from the progenitor, a cool red giant

  $\dot{M}$(wind) ≈ $10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ for 2000 years
  $\dot{v}$(wind) ≈ 15 km s^{-1}

- central star T_* hot $> 10^5$ K
  → He, C, O are ionized, T_{gas} (PN) ~12,000K

  c.f., T_{gas}(H II) ~7,000K to 10,000 K

Massive stellar wind

$$\dot{v}(\text{wind}) \sim 1500 - 3000 \text{ km s}^{-1}$$

When $P_w = \rho_w \, v_w^2 \;\rightarrow\; P_{\text{thermal}}^{\text{cloud}}$

➔ shocks into and sweeps up the ISM

➔ a reverse shock, slowing down the wind