Ionization Processes

- Photoionization
- Auger ionization

    an inner-shell electron is photoionized → a higher-level electron fills in → releasing a photon, or energy transferred to an electron → excited or ionized of an Auger electron

- Collisional ionization
- Cosmic Ray Ionization

    non-thermal electrons and ions

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 completely photoionized, He mostly singly ionized, O and Ne doubly ionized (so 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 $N(H\ I) \lesssim 10^{17}\ \mathrm{cm}^{-2}$, 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

(iii) **Forbidden lines**

Resonance-fluorescence

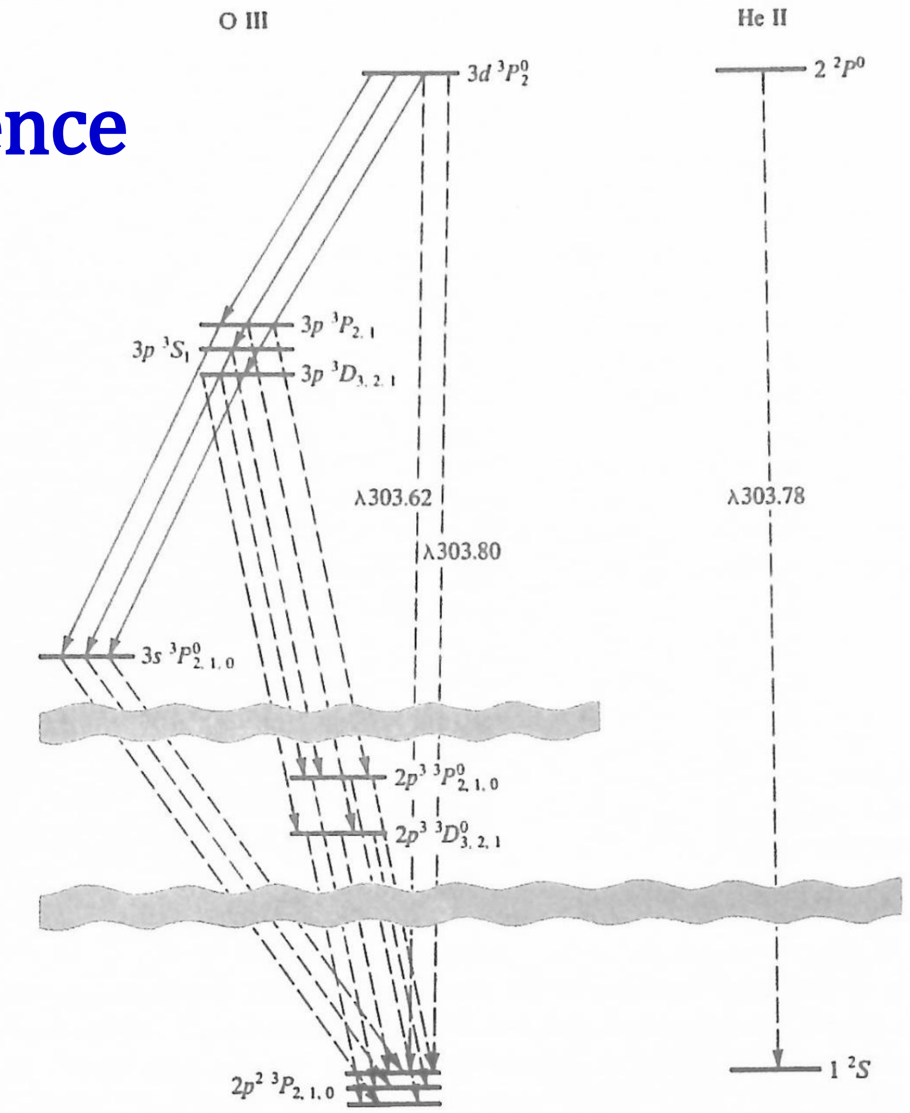
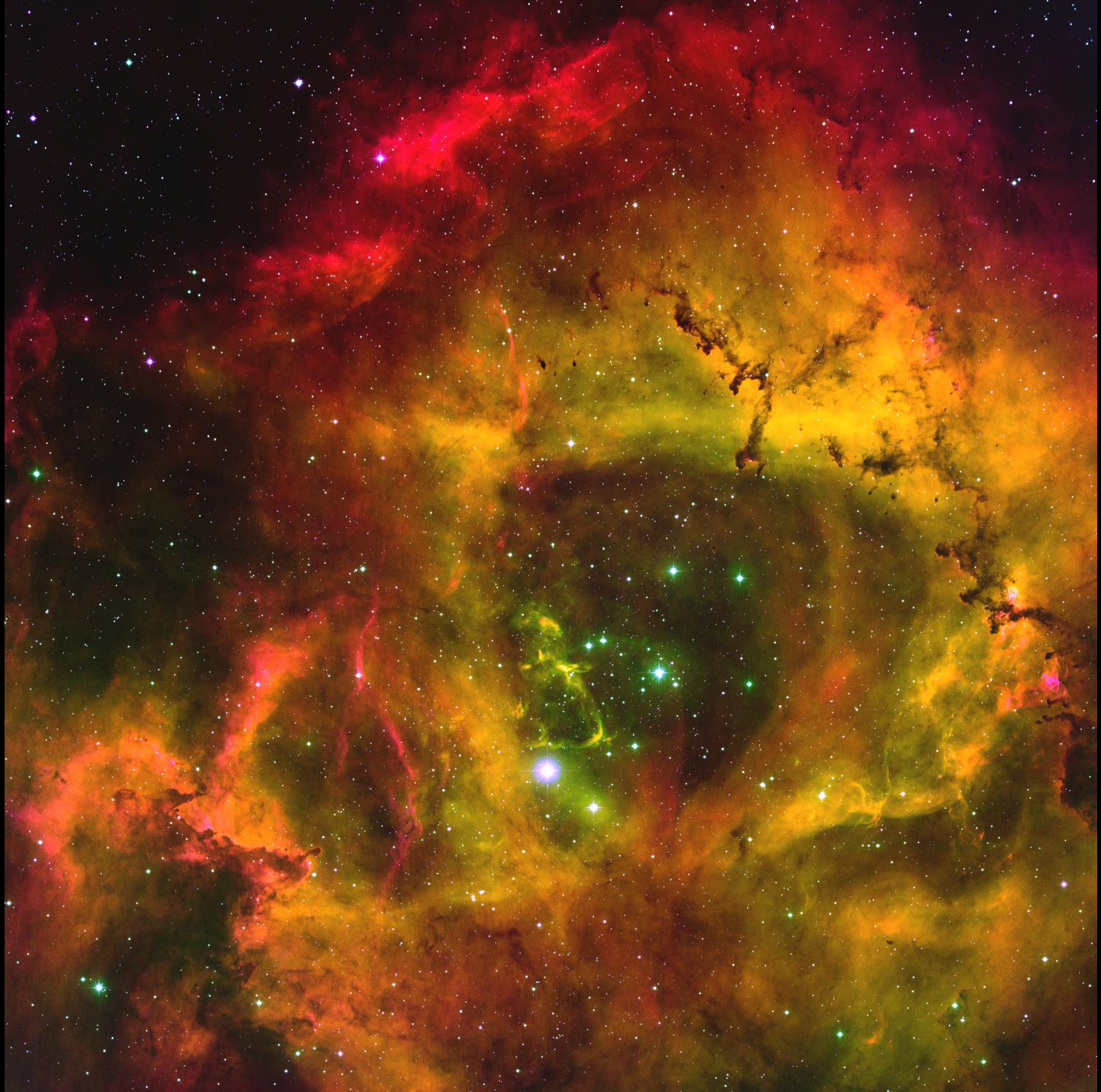


FIGURE 4.6
Schematized partial energy-level diagrams of [O III] and He II showing coincidence of He II Lα and [O III] $2p^2\ ^3P_2$ – $3d\ ^3P_2^0$ λ303.80. The Bowen resonance-fluorescence lines in the optical and near-ultraviolet are indicated by solid lines, and the far ultraviolet lines that lead to excitation or decay are indicated by dashed lines.

Rosette Nebula and NGC 2244 (H II)



Red: H-alpha
Blue: [S II]
Green: [O III]

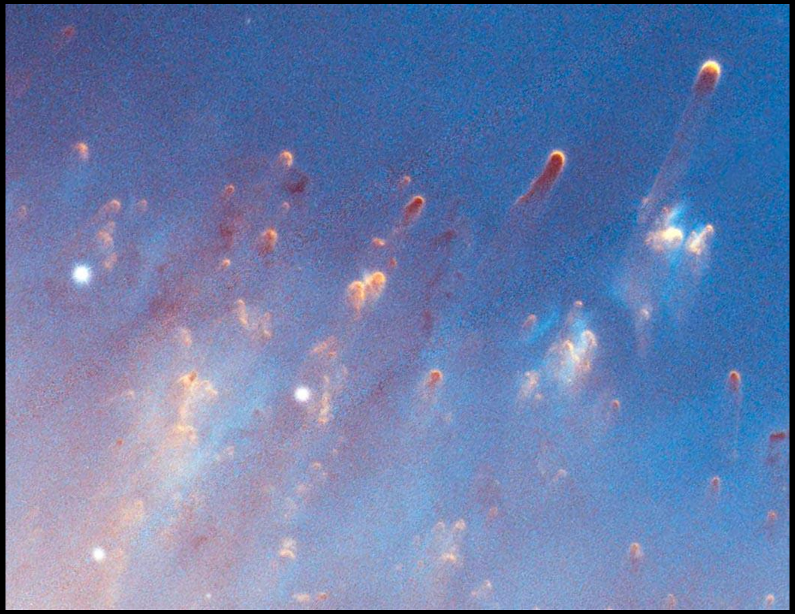
Trifid Nebula
(M20)
(H II)

Ring Nebula
(M57)
(PN)

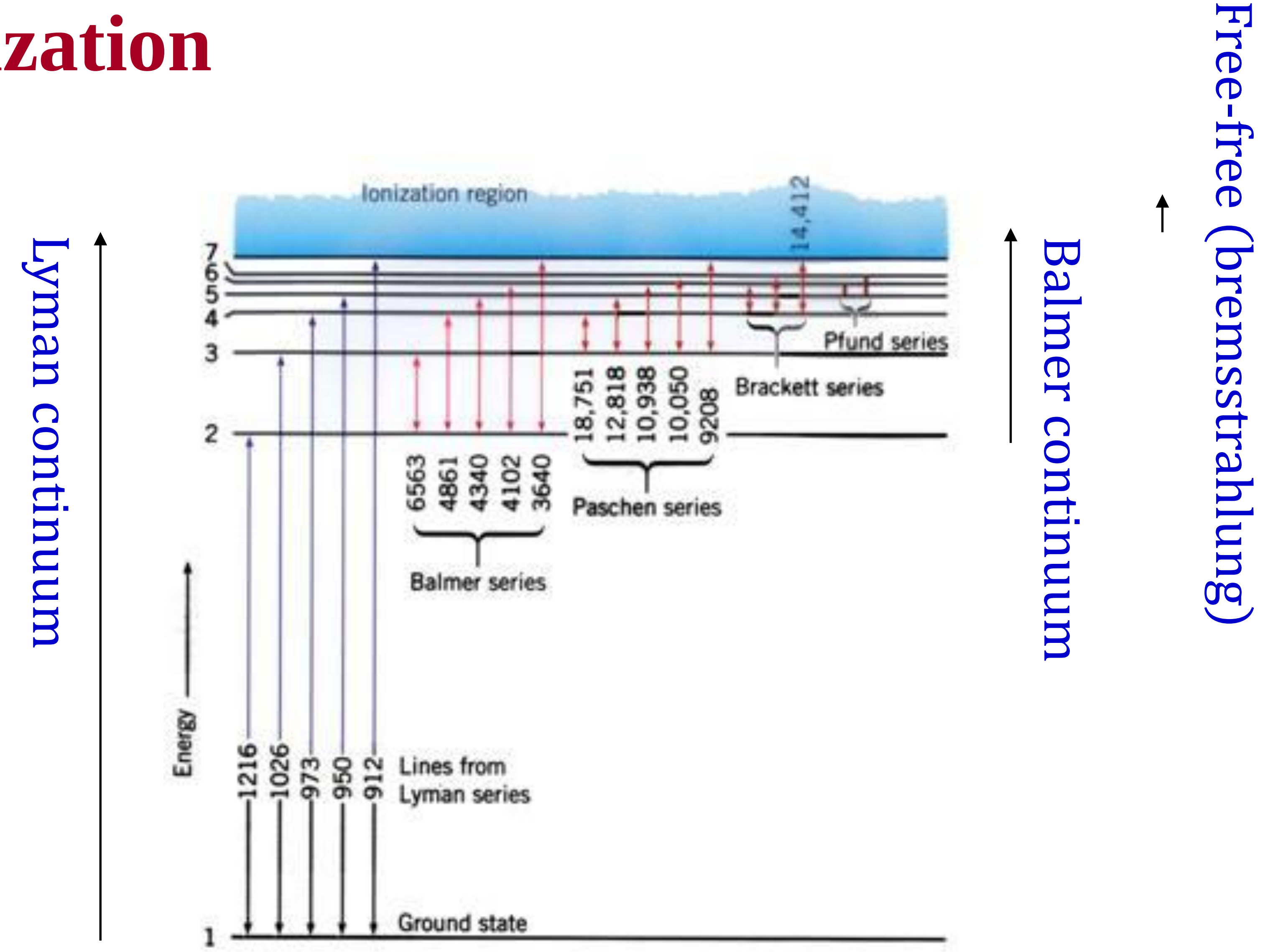
Blue: He
Green: O
Red: N
WD 120,000 K

Helix Nebula (NGC 7293) (PN)

Photoionized cometary knots

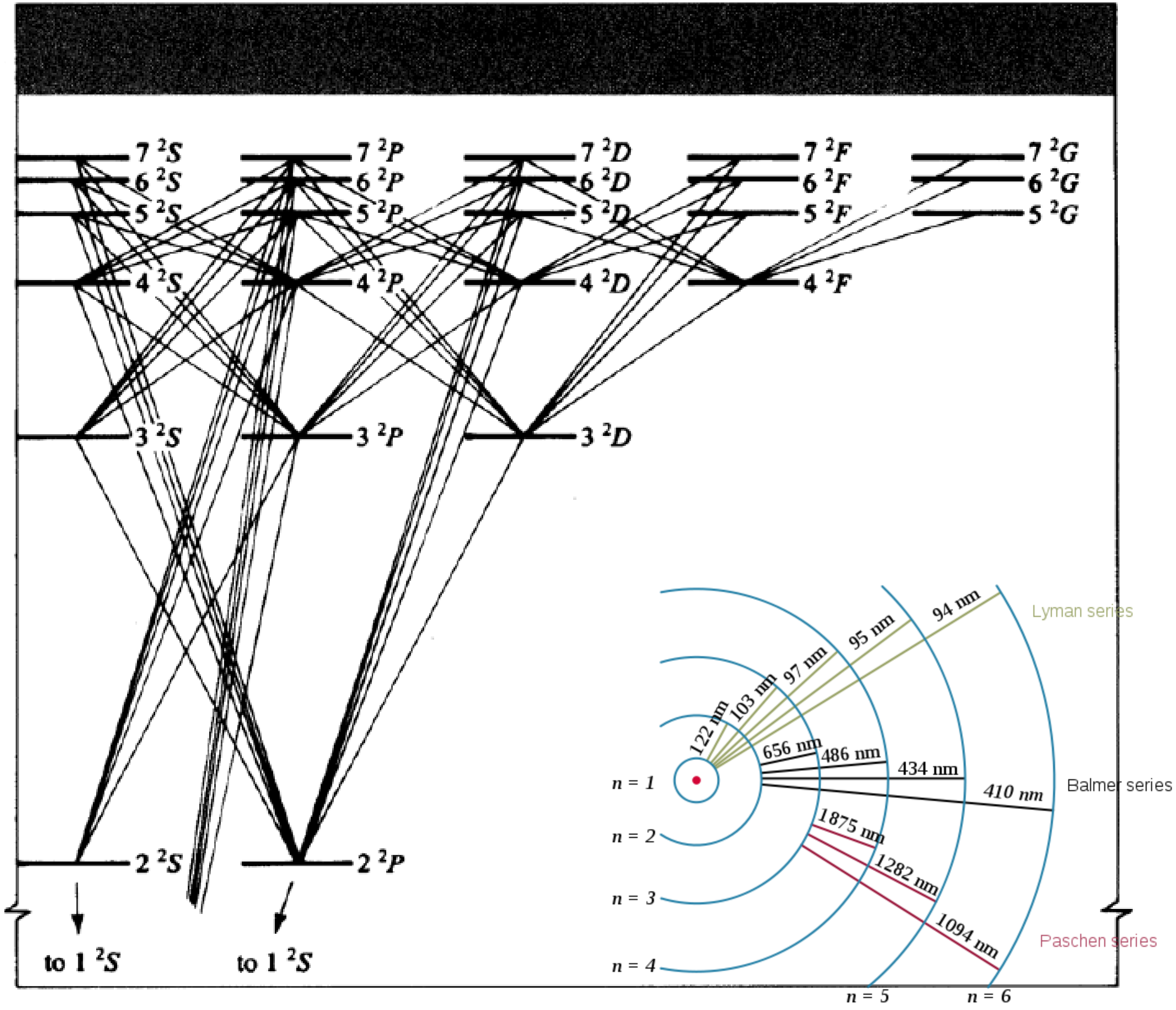


Photoionization



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

Hydrogen spectrum --- permitted transitions

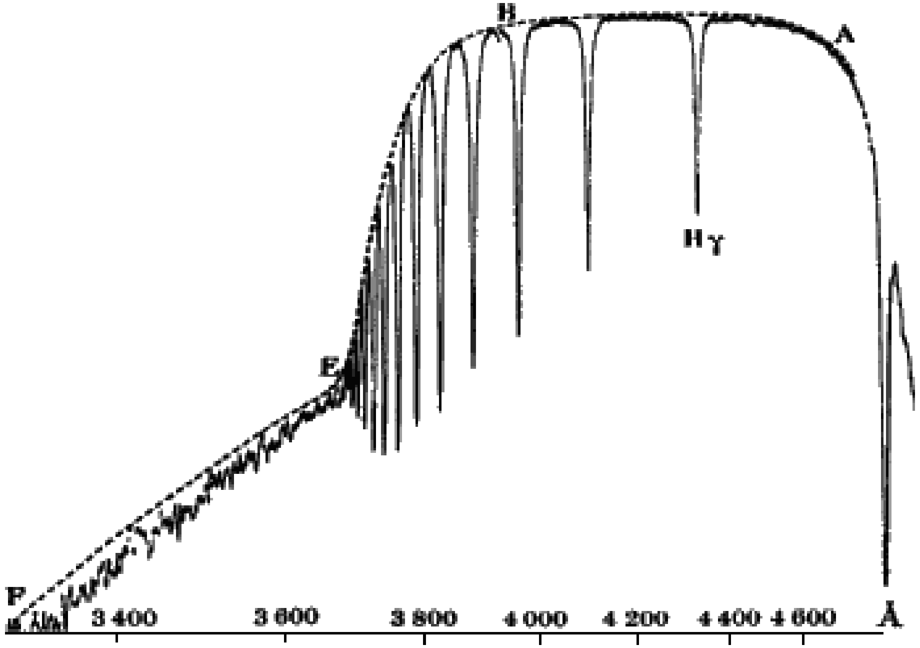


Wavelengths of important H Lines

- 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

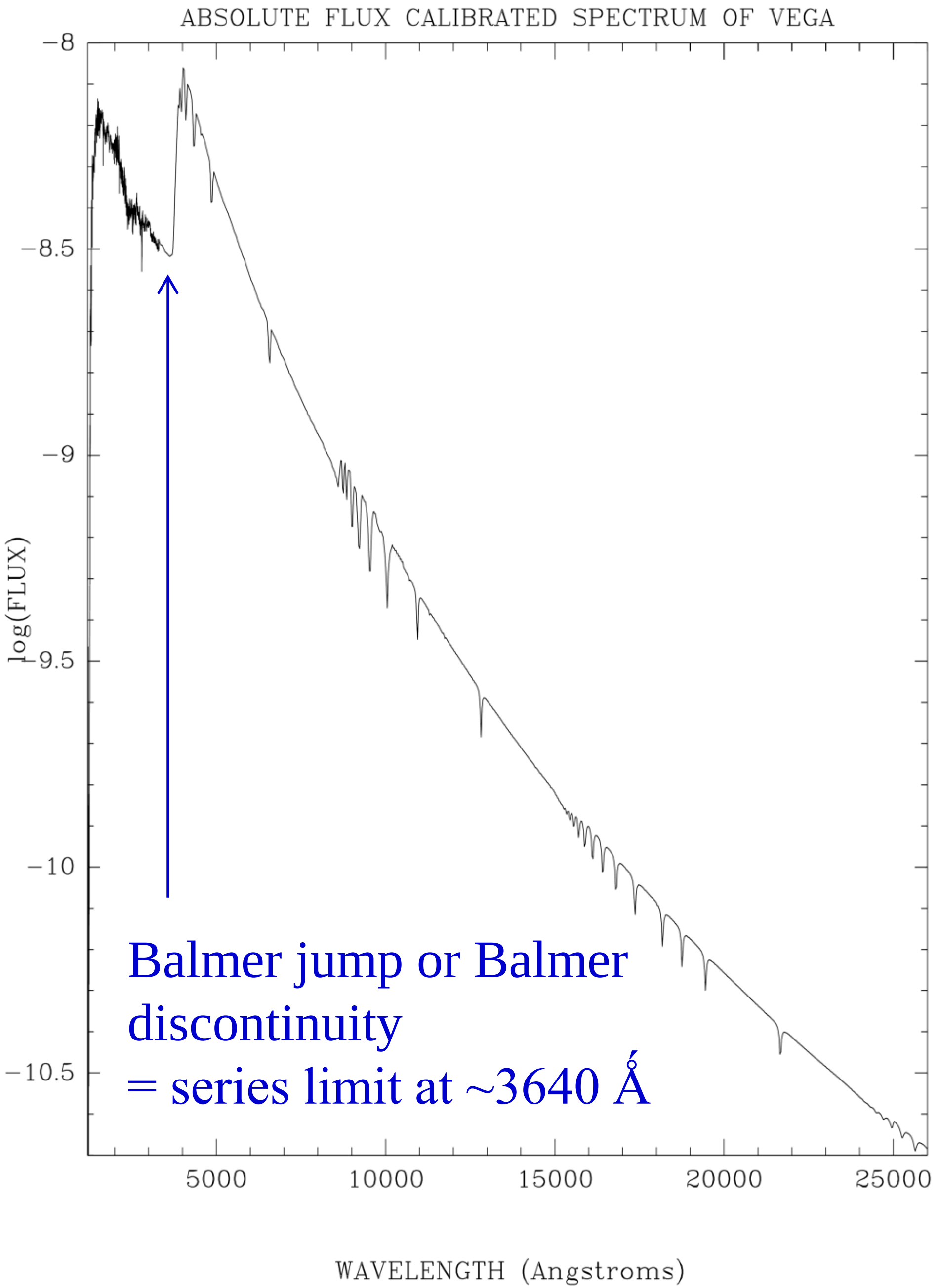


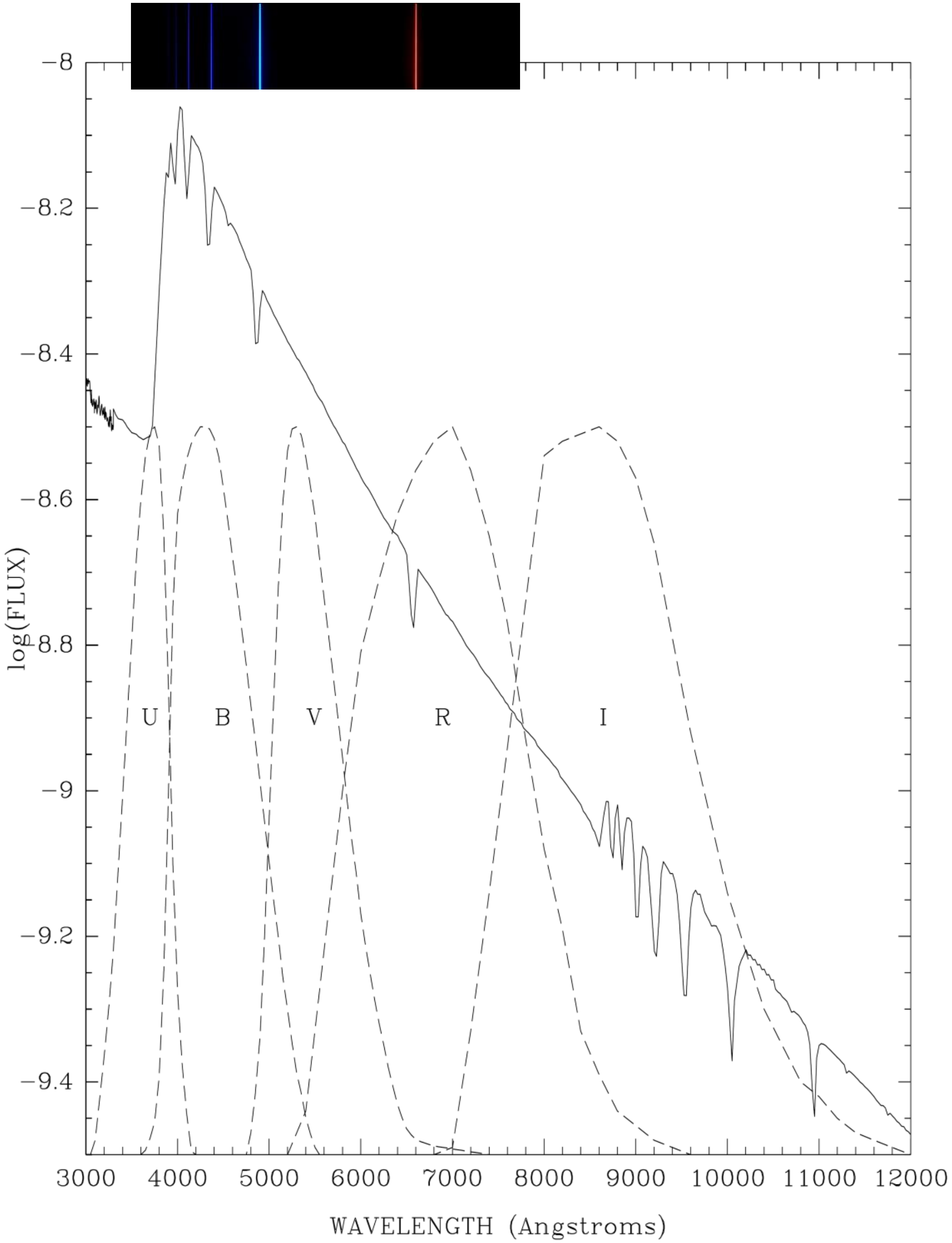
the spectra of the hot star alpha Lyra (Vega) (Barbier & Chalonge, 1939)

Instrument Science Report CAL/SCS-008

Absolute Flux Calibrated Spectrum of Vega

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

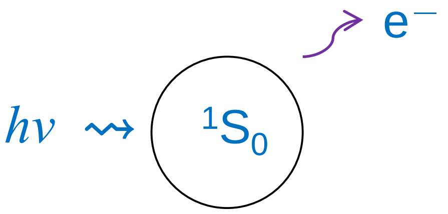



log(FLUX)
−8
−8.2
−8.4
−8.6
−8.8
−9
−9.2
−9.4
U
B
V
R
I
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
WAVELENGTH (Angstroms)

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

- Absorption $(0 \rightarrow 1)$
  ➔ B_{01} or oscillator strength f_{10}
- Emission $(1 \rightarrow 0)$
  ➔ A_{10}

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



Probability of **photoionization**

→ photoionization cross section

$H + h$º → $H^+ + e$

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

$h\nu_1 = Z^2 h\nu_0 = 13.6\, Z^2$ 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.

PHILOSOPHICAL TRANSACTIONS

OF THE

ROYAL SOCIETY OF LONDON.

SERIES A, VOL. 229. Pp. 163-204.

CONTINUOUS ABSORPTION.

BY

J. A. GAUNT,

TRINITY COLLEGE, CAMBRIDGE.

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V. *Continuous Absorption.*

By J. A. GAUNT, *Trinity College, Cambridge.**

(*Communicated by* R. H. FOWLER, *F.R.S.*)

(Received January 3, 1930—Read February 6, 1930.)

§ 1. *Introduction.*

For some years astrophysicists have been looking for an adequate theory of continuous—as opposed to line—absorption. The natural and generally accepted mechanism is the transition of an electron from a bound state to a free state, or from one free state in the neighbourhood of an ion to another free state of greater energy. The theory hitherto used is KRAMERS' theory† of the converse process of emission by a free electron passing a positive nucleus. Since emission and absorption are intimately connected by thermodynamics, the absorption coefficient can be calculated from KRAMERS' formulæ.‡ Unfortunately, although KRAMERS' work is in good agreement with laboratory observations of X-rays, it gives an absorption coefficient many times smaller than that found from astronomical observations.

KRAMERS used classical electromagnetism, and got over the difficulty of the quantisation of negative energies by distributing the classical emission that involved captures somewhat arbitrarily among the various stationary states. It was evidently desirable to do the same work by means of quantum theory, both for the sake of greater rigour, and in the hope of finding a larger absorption. The foundations of such a theory were laid by OPPENHEIMER,|| upon the bed-rock of SCHRÖDINGER's equation, in a paper to which this one is much indebted. The matrix-elements involving positive energies present considerable difficulty, and the approximations used by OPPENHEIMER in his paper of 1927 are unsuitable for stellar applications.

The present work carries the theory further, though not to completion. It contemplates absorption by an electron in an encounter with a positive nucleus, or by an electron bound to the nucleus. Interference by other electrons is not considered. In the

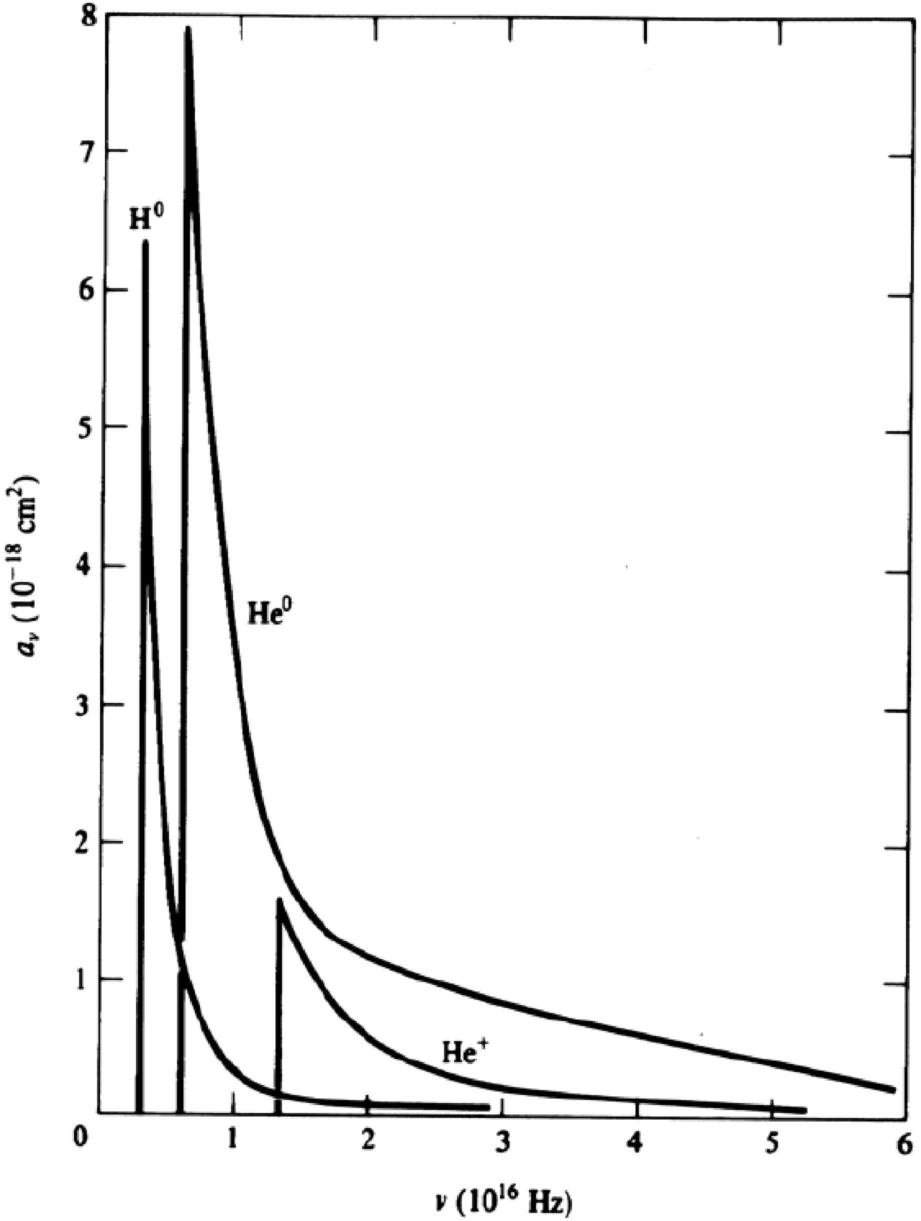
* As Mr. GAUNT has left Europe, this paper has been seen through the press by Dr. DIRAC and Mr. R. H. FOWLER. They trust they have done justice to the author's work. Any communications on the subject matter covered by this paper should be addressed to one or other of them.

† KRAMERS, 'Phil. Mag.,' vol. 46, p. 836 (1923).

‡ EDDINGTON, 'Internal Constitution of the Stars,' p. 229 (1926); MILNE, 'M.N.R.A.S.,' vol. 85, p. 750 (1925). Referred to as M I.

|| OPPENHEIMER, 'Z. Physik,' vol. 41, p. 768 (1927). Referred to as O I.

Photoionization cross sections for H, He and He^+



No reaction until a critical frequency; then drops off as the 3rd power with frequency

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

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

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

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

[# of ionization] $\rm s^{-1} atom^{-1}$ 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

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

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

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.

$\alpha^{(1)} = \sum_{n=1}^{\infty} \alpha_n = 6.82 \times 10^{-13}$ 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 (in $cm^3\ s^{-1}$) $\alpha_n\ {}^2L$ for H

	5,000 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}	2.34×14^{-14}	1.60×10^{-14}
$\alpha_{2\ ^2P^o}$	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}
$\alpha_{3\ ^2P^o}$	3.17×10^{-14}	2.04×10^{-14}	1.23×10^{-14}
$\alpha_{3\ ^2D}$	3.43×10^{-14}	1.73×10^{-14}	9.49×10^{-15}
$\alpha_{4\ ^2S}$	5.23×10^{-15}	3.59×10^{-15}	2.40×10^{-15}
$\alpha_{4\ ^2P^o}$	1.51×10^{-14}	9.66×10^{-15}	5.81×14^{-15}
$\alpha_{4\ ^2D}$	1.90×10^{-14}	1.08×10^{-14}	5.68×10^{-15}
$\alpha_{4\ ^2F^o}$	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}	4.0×10^{-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}	1.43×10^{-13}

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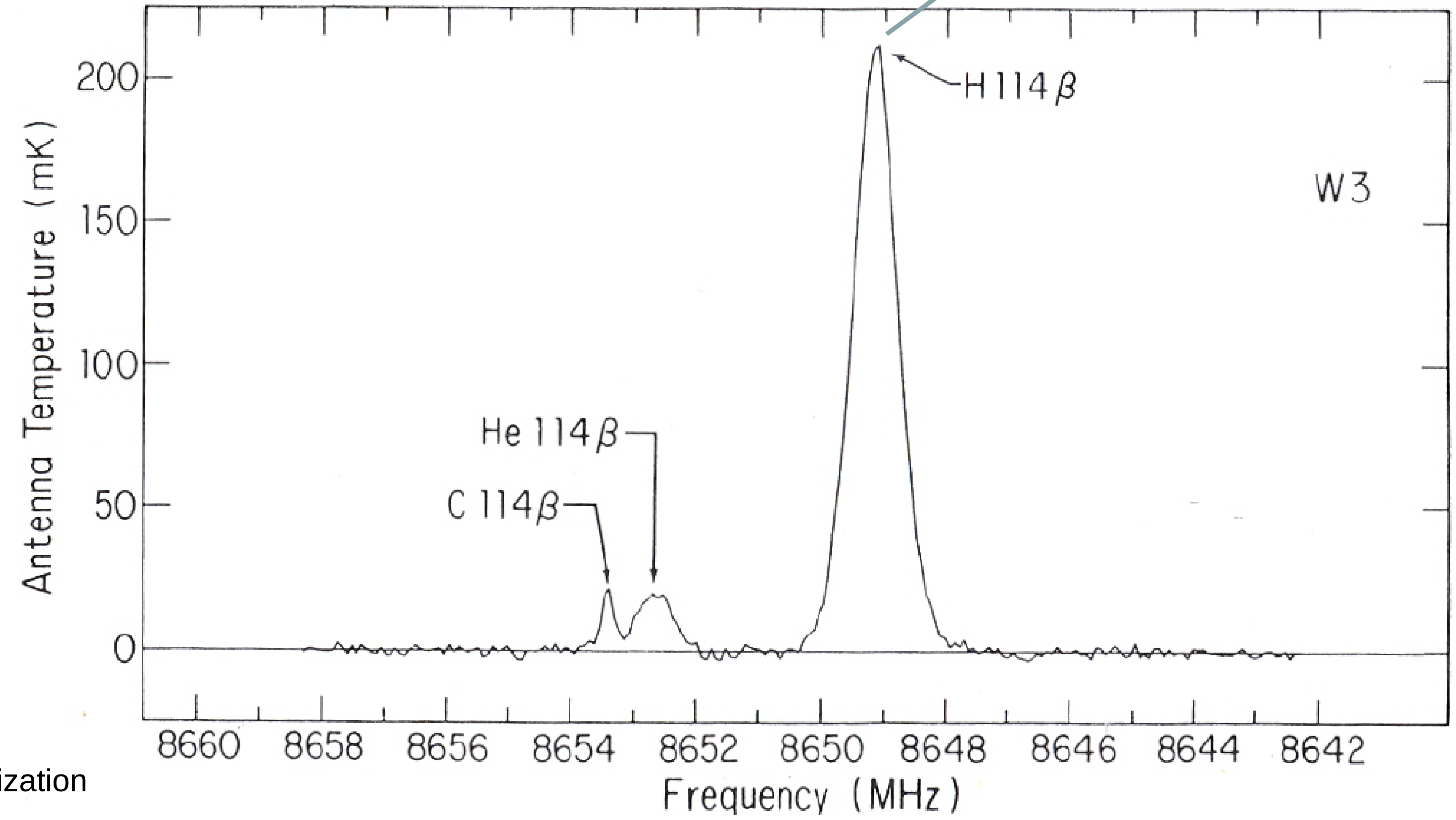
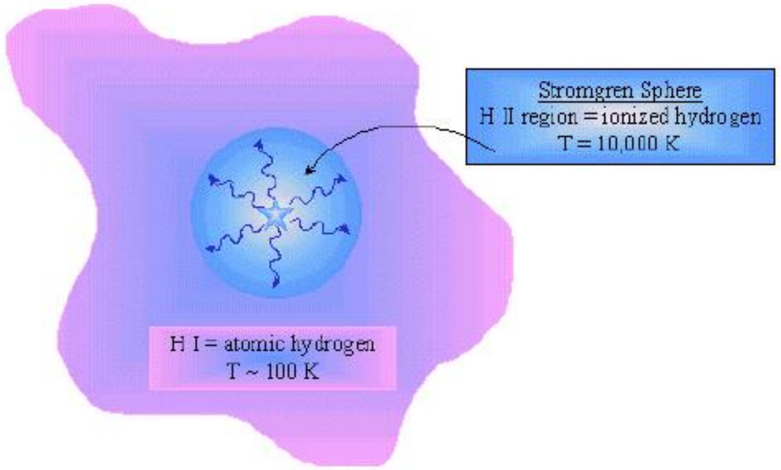
Recombination → photons

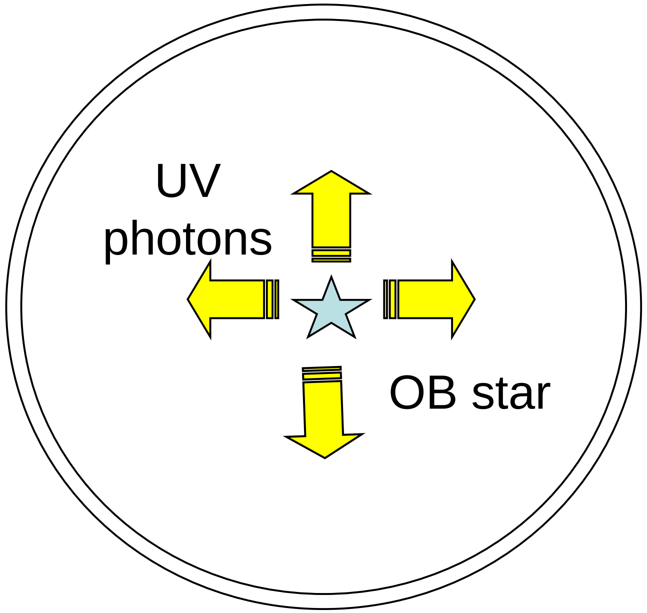
Some of the photons can ionize or excite other species

H 114 β: $n = 116 \rightarrow 114$



H II regions





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

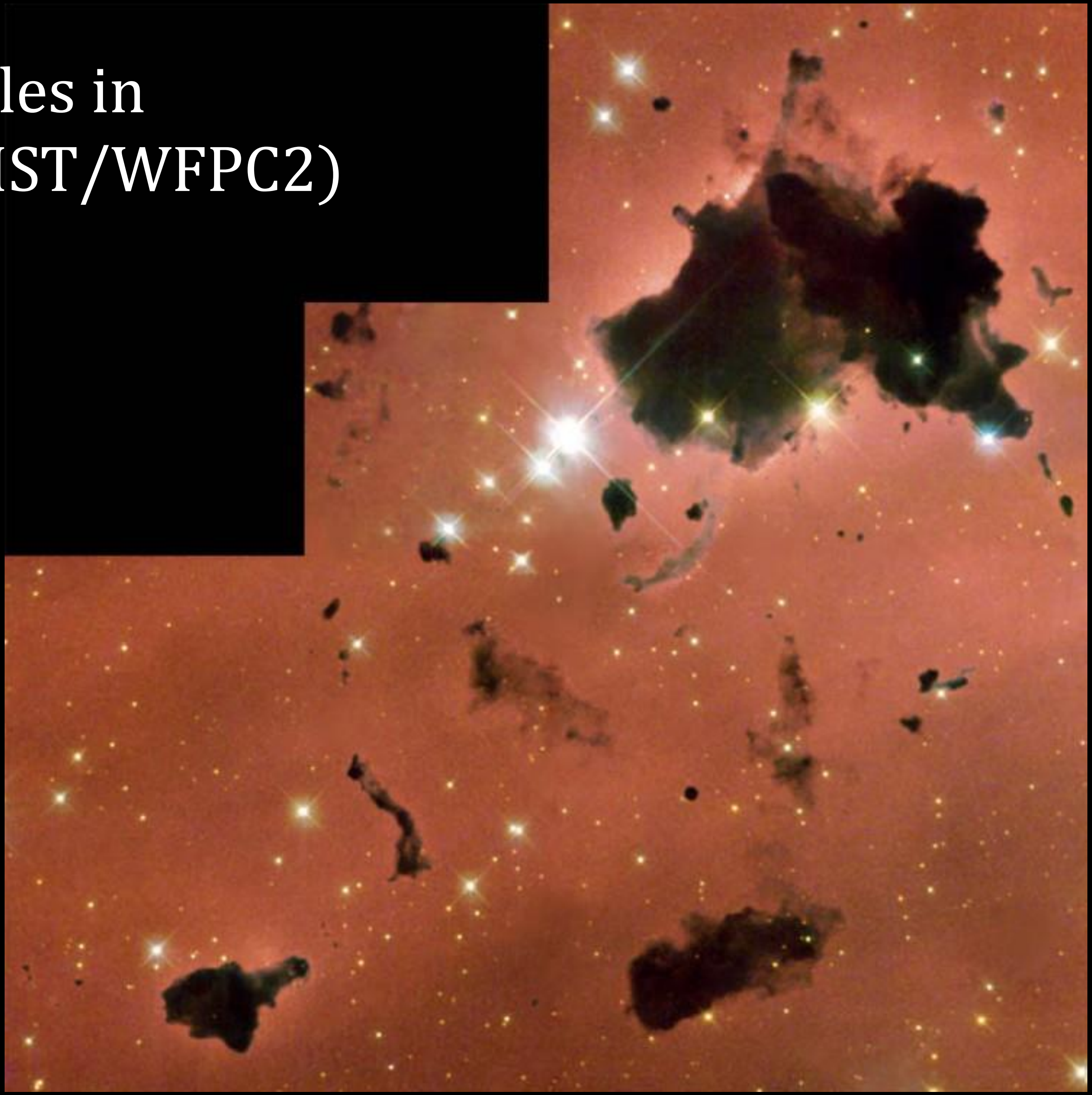
If e already in an excited state, a longer λ will do

Collisional ionization negligible in HII regions

Once ionized, the e recombines with p, emitting Balmer, Paschen, Pfund lines or 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

Table 2.3

Calculated Strömgren radii as function of spectral types spheres

Spectral type	T_* (K)	M_V	log $Q(H^0)$ (photons/s)	log $n_e n_p r_1^3$ n in cm^{-3}; r_1 in pc	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}
O3 V	51,200	−5.78	49.87	49.18	6.26	122
O4 V	48,700	−5.55	49.70	48.99	6.09	107
O4.5 V	47,400	−5.44	49.61	48.90	6.00	100
O5 V	46,100	−5.33	49.53	48.81	5.92	94
O5.5 V	44,800	−5.22	49.43	48.72	5.82	87
O6 V	43,600	−5.11	49.34	48.61	5.73	81
O6.5 V	42,300	−4.99	49.23	48.49	5.62	75
O7 V	41,000	−4.88	49.12	48.34	5.51	69
O7.5 V	39,700	−4.77	49.00	48.16	5.39	63
O8 V	38,400	−4.66	48.87	47.92	5.26	57
O8.5 V	37,200	−4.55	48.72	47.63	5.11	51
O9 V	35,900	−4.43	48.56	47.25	4.95	45
O9.5 V	34,600	−4.32	48.38	46.77	4.77	39
B0 V	33,300	−4.21	48.16	46.23	4.55	33
B0.5 V	32,000	−4.10	47.90	45.69	4.29	27
O3 III	50,960	−6.09	49.99	49.30	6.38	134
B0.5 III	30,200	−5.31	48.27	45.86	4.66	36
O3 Ia	50,700	−6.4	50.11	49.41	6.50	147
O9.5 Ia	31,200	−6.5	49.17	47.17	5.56	71

Note: $T = 7{,}500$ K assumed for calculating α_B.

Osterbrock

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

Ex: An O7.5 star, with an effective temperature of 40,000 K emits $\log N_{\mathrm{Ly}} = 49.0$ photons per second, where $N_{\mathrm{Ly}} = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu}\, \mathrm{d}\nu$ is the number of Lyman photons, i.e., photons more energetic than $\nu_0 = 3.29 \times 10^{15}\ \mathrm{s}^{-1}$ or $\lambda_0 = 912$ Å. Assuming the H^+ region has a temperature of 10,000 K, and a number density of $10\ \mathrm{cm}^{-3}$, estimate the size of the ionizing region.

Osterbrock p.25

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	5,000 K	10,000 K	20,000 K
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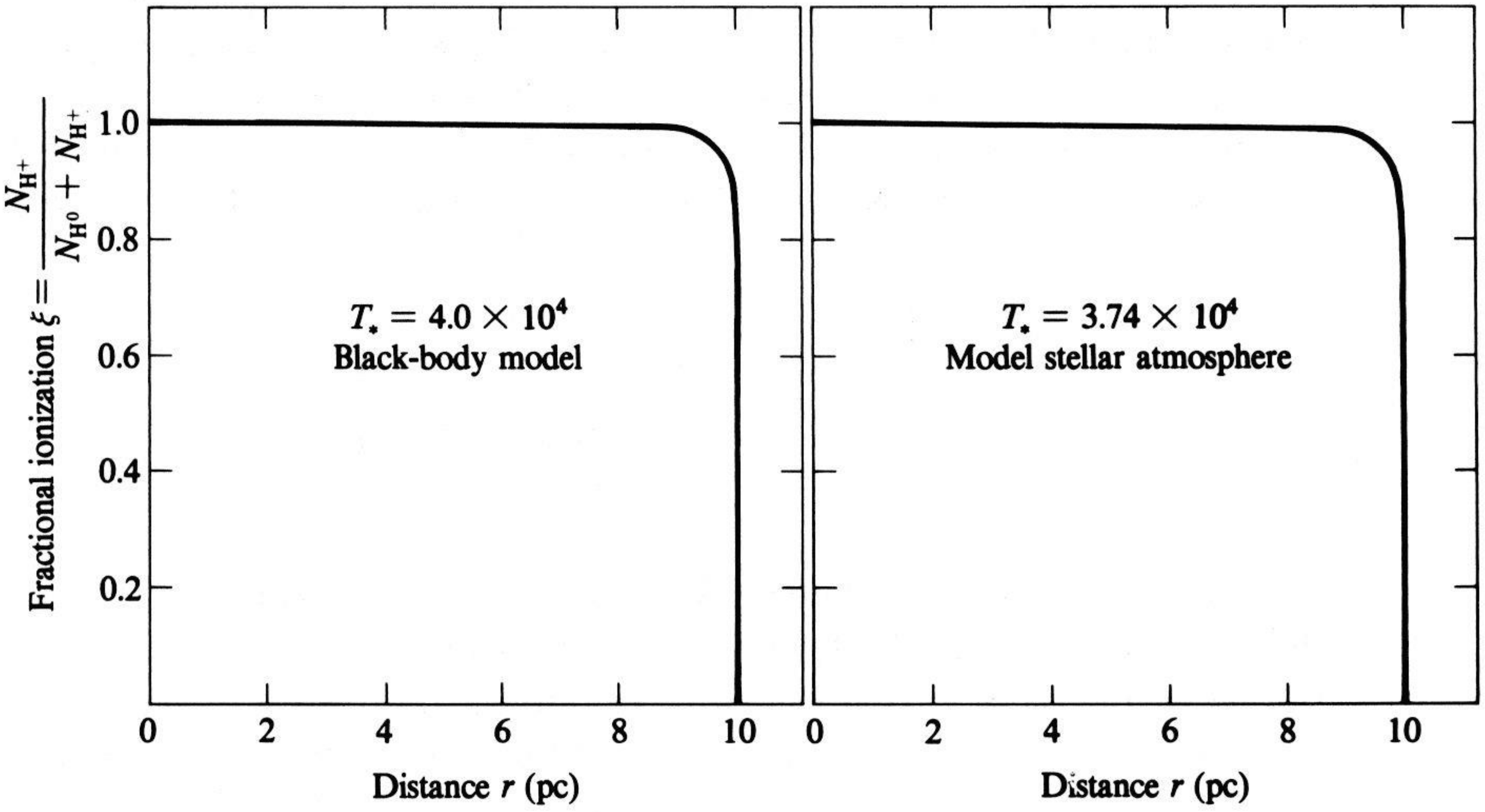

FIGURE 2.3
Ionization structure of two homogeneous pure-H model H II regions.

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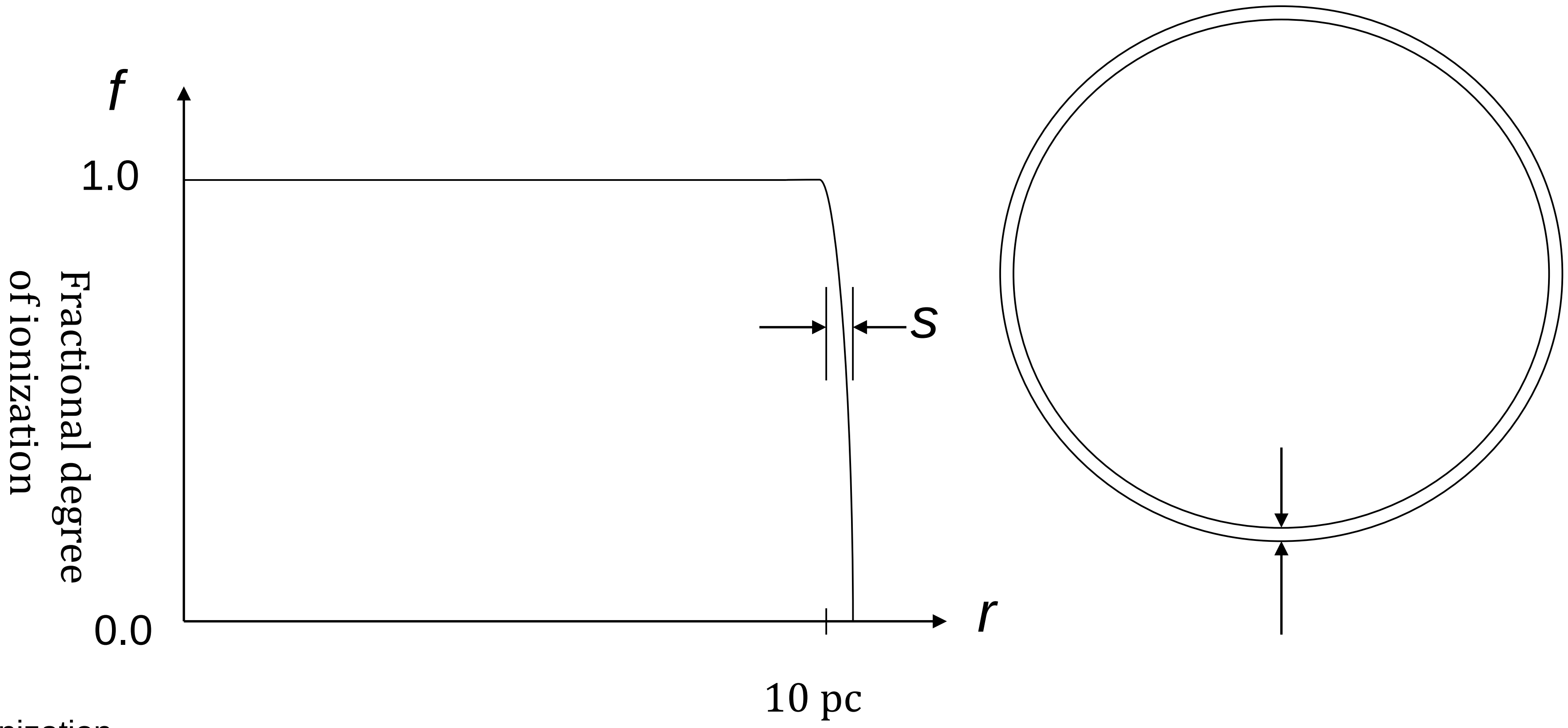
Take $T_* = 40,000$ K (i.e., O6 V), $n_H = 10$, $R_s \approx 1$ pc, then $R_s \approx 10$ pc

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!

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 $\uparrow\uparrow$ → H II region expands, v~ 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 (ionization) 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.

  → H II regions are <u>expanding</u>!

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 plus a developing H II region
= an IR source embedded in an H II 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 → **E** field and **B** field
- Each H II region may contain many OB stars.
- A **compact** H II region = young

  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

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

- 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