Lecture 7

stellar atmospheres

prof. Marcos Diaz

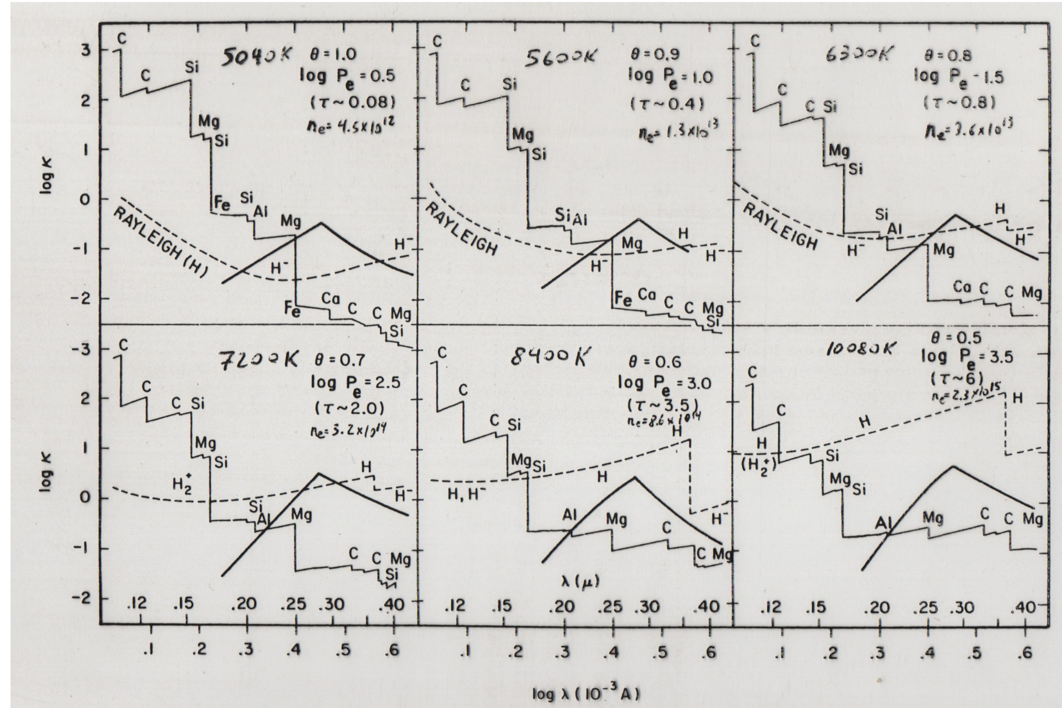
treasure map:

Gray: pg 147

H&M: pg 144, 187

Erika: pg 68

Rutten: pg 94



from Matsushima 1973

The continuum
scattering, absorption and emission

I.a Thomson or "electron" scattering:

- *elastic or coherent*
- *cross-section* σ_T *independent of photon energy*
- *dipole phase-function*
- *preserve photon number*
- *valid for* $h\nu << m_e c^2$
- *often important in ionized medium*

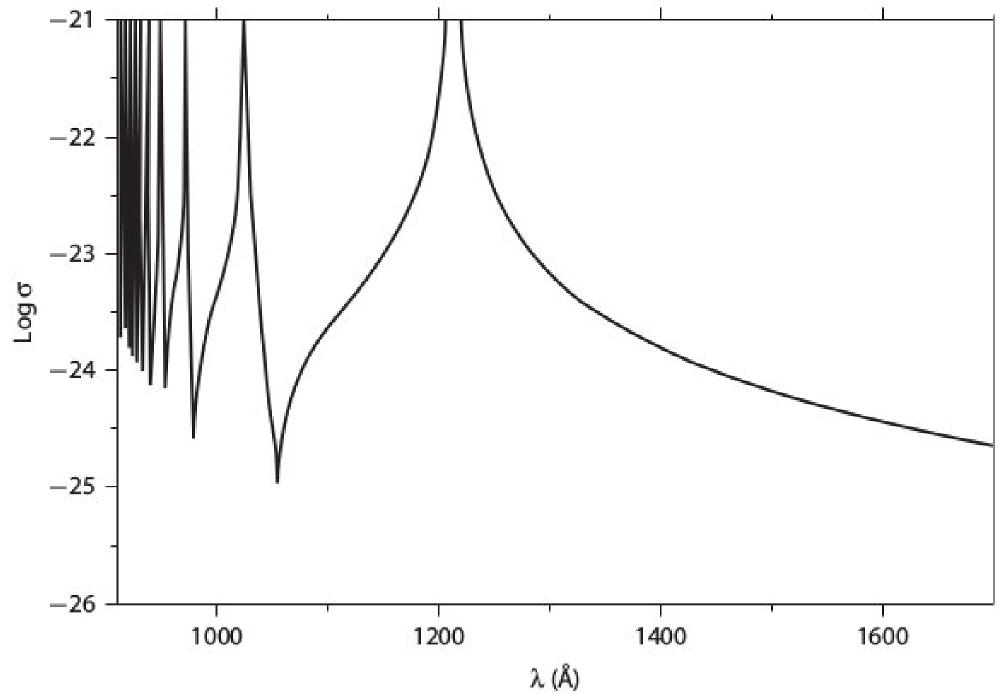
$$\sigma(\omega) \rightarrow \sigma_T \equiv \frac{8\pi e^4}{3m_e^2 c^4} = 6.65 \times 10^{-25} \text{ cm}^2$$

I.b Rayleigh scattering:

- *elastic or coherent*
- *cross-section dependent of photon energy*
- *dipole phase-function*
- *scattering by atoms and molecules (neutral H)*
- *conserve photon number*

$$\sigma_{\mathrm{Ray}}(\omega) \propto \frac{\sigma_{\mathrm{T}}\omega^4}{(\omega_{ij}^2 - \omega^2)^2} \rightarrow \sigma_{\mathrm{T}} \left(\frac{\omega}{\omega_{ij}}\right)^4 \quad [\mathrm{cm}^2]$$

I.c Rayleigh scattering (cont):

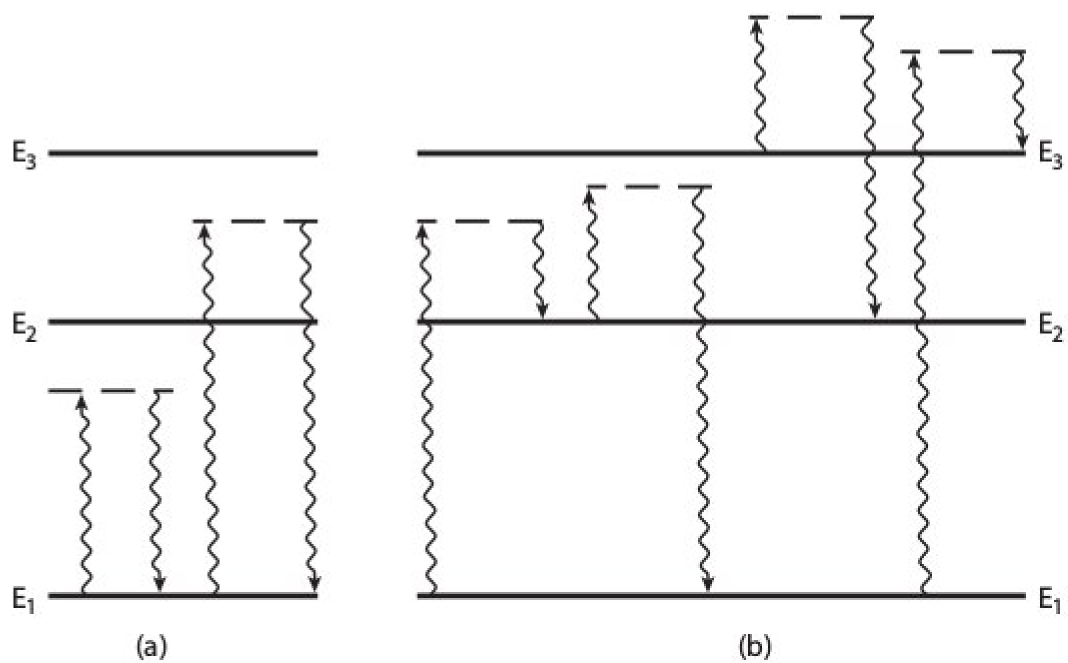


Rayleigh cross-section for H (from Hubeny & Mihalas 2015)

$$\sigma_{\mathrm{Ray}}(\omega) \approx \sigma_{\mathrm{T}} \left(\sum_j \frac{f_{1j}\omega^2}{\omega_{1j}^2 - \omega^2} \right)^2 \ [\mathrm{cm}^2]$$

I.d Raman "cascading" scattering:

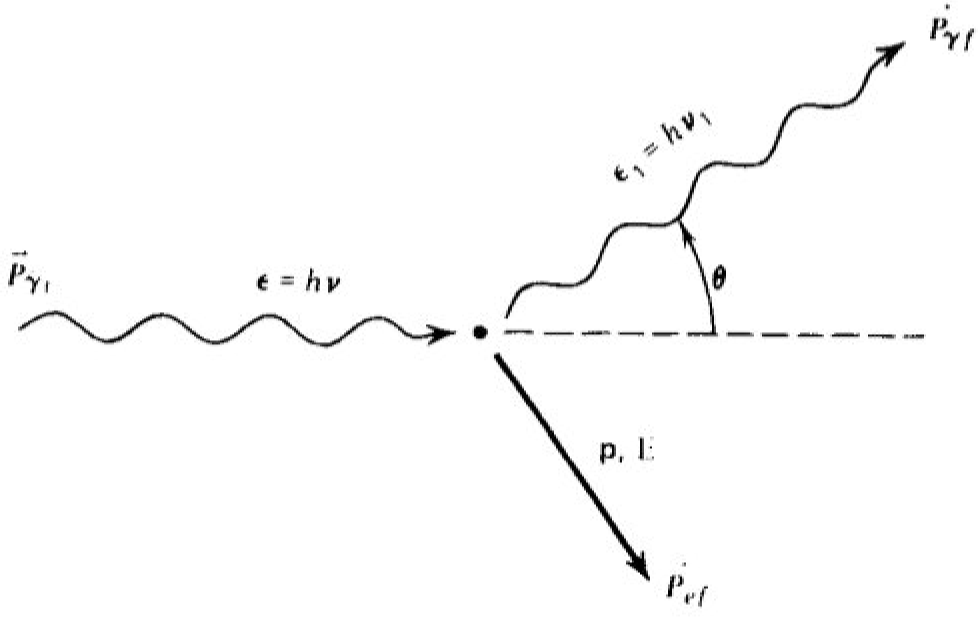
- *inelastic and non-coherent*
- *cross-section dependent of photon energy*
- *complex phase-function*
- *scattering by atoms and molecules (neutral H)*
- *do not conserve photon number*



Rayleigh (a) vs. Raman (b) scattering of continuum photons (from Hubeny and Mihalas 2015)

I.e Compton scattering:

- *inelastic or noncoherent*
- *cross-section dependent of photon energy*
- *anisotropic, symmetric*
- *scattering by charged particles*
- *conserve photon number*
- *depart from Thomson for* $h\nu \sim m_e c^2$



Ie. Compton scattering (cont.):

the differential Klein-Nishina cross-section

$$\sigma_{\rm KN}(\theta) = \frac{3}{4}\sigma_{\rm T}\left(\frac{\nu}{\nu'}\right)^2\left(\frac{\nu'}{\nu} + \frac{\nu}{\nu'} - \sin^2\theta\right)$$

(per unit solid angle)

(with)

$$\frac{4}{3}\frac{\sigma_{\rm KN}(x)}{\sigma_{\rm T}} = \frac{1+x}{x^3}\left[\frac{2x(1+x)}{1+2x} - \ln(1+2x)\right] + \frac{\ln(1+2x)}{2x} - \frac{1+3x}{(1+2x)^2}$$

$$x \equiv h\nu'/m_e c^2$$

II.a Bremsstrahlung (free-free)

thermal absorption: α_ν^{ff}

thermal *f-f* emission: $\eta_\nu^{ff} = \alpha_\nu^{ff} B_\nu$

$$\alpha_\nu^{ff} = 3.7 \times 10^8 T^{-1/2} Z^2 n_e n_i \nu^{-3} (1 - e^{-h\nu/kT}) \bar{g}_{ff}$$

(linear abs. coef.)

with Rosseland mean:

$$\alpha_R^{ff} = 1.7 \times 10^{-25} T^{-7/2} Z^2 n_e n_i \bar{g}_R$$

II.b Phoionization / Radiative recombination (bound-free)

absorption coef.: $\alpha_\nu^{bf} - \alpha_{\nu\, IND}^{bf}$

b-f rad. rec. emission (LTE):

$$\eta_\nu^{bf} = \left(\alpha_\nu^{bf} - \alpha_{IND}^{bf}\right) B_\nu$$

$$\alpha_{\rm bf}(n', \nu) = \frac{64\pi^4 Z^4 m_e e^{10} g_{\rm bf}(n', \nu)}{3\sqrt{3} c h^6 n'^5 \nu^3} \equiv \mathcal{K} \frac{Z^4}{n'^5 \nu^3} g_{\rm bf}(n', \nu)$$

(Kramers hydrogenic * Gaunt factor)

where n´ is the excitation level and ν is the frequency above threshold.

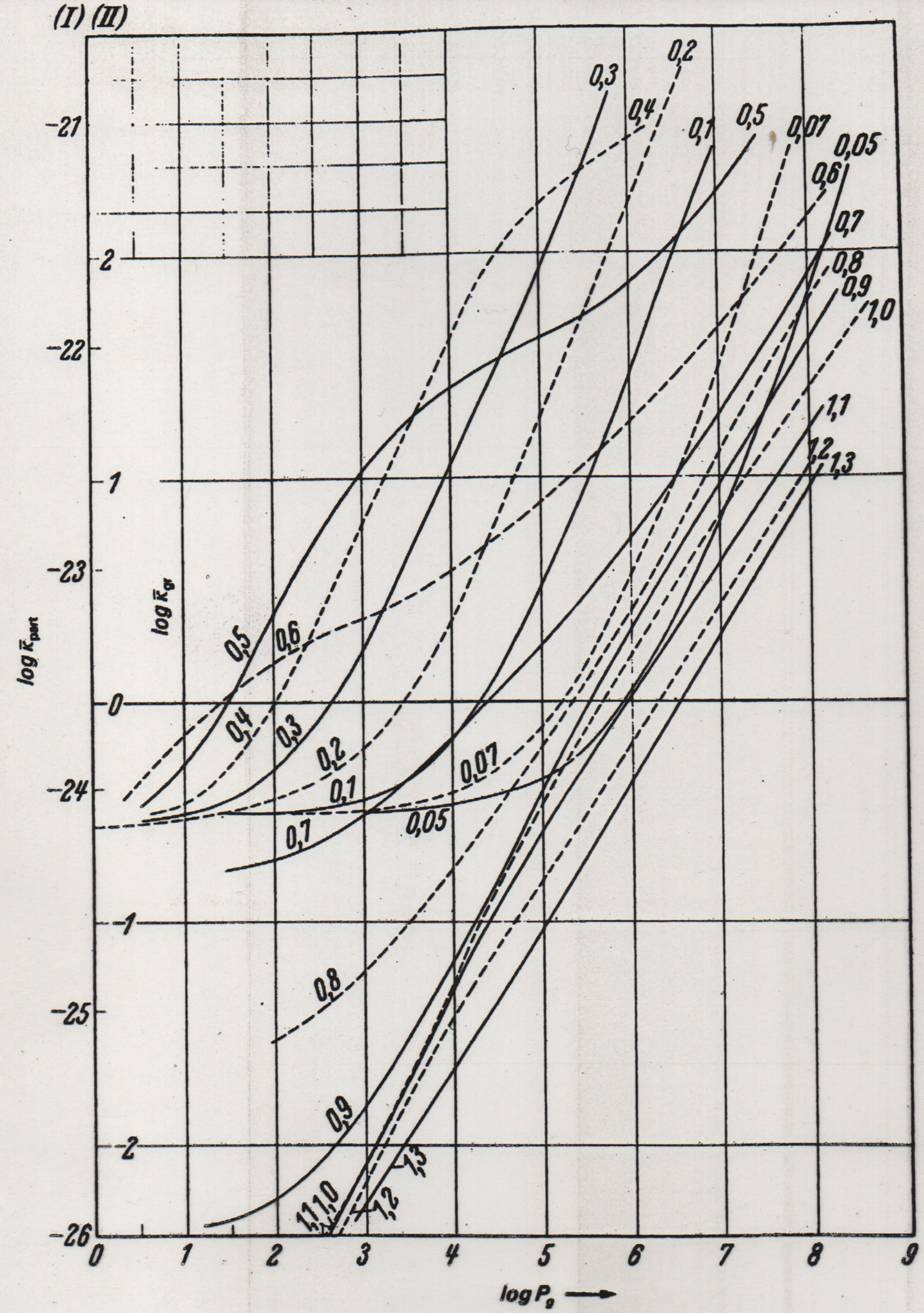


Fig. 8.7. The Rosseland mean values $\bar{\kappa}_R$ for the continuous absorption coefficient are shown as a function of the gas pressure. Each curve corresponds to a given value of the temperature. The value of $\Theta = 5040/T$ is given for each curve. The plot is double logarithmic. What is shown is actually the absorption coefficient per gram of material, i.e., for a column of gas which contains one gram of material, or per heavy particle, as shown on the outer left-hand scale. Solar element abundances were assumed.

(from Bohn-Vitense 1989)

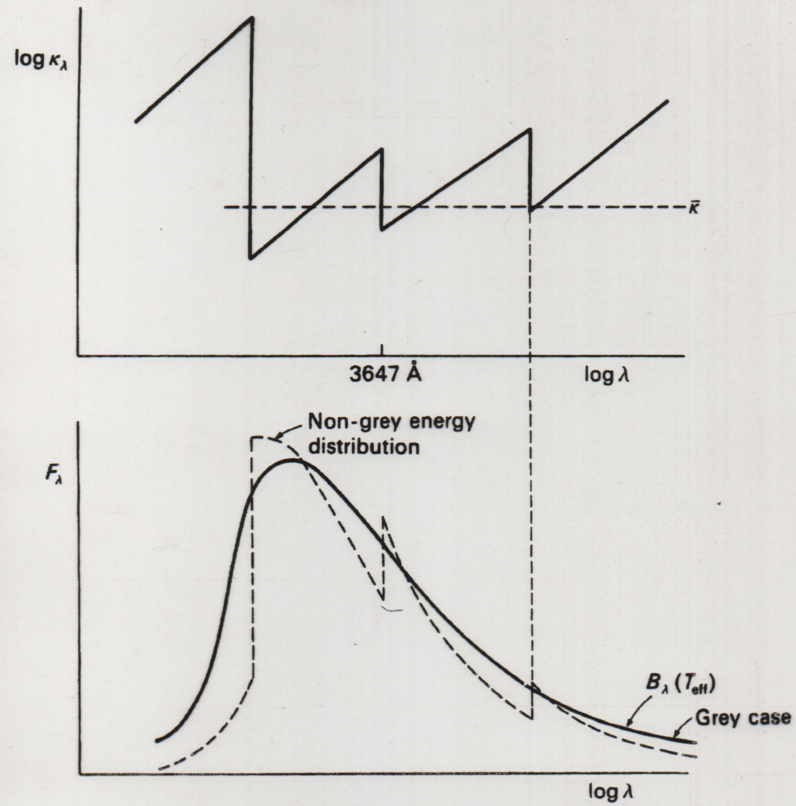


Fig. 8.2. Schematic diagram showing the influence of the non-greyness of the hydrogen absorption coefficient on the observed energy distribution of the star.

(from Bohn-Vitense 1989)

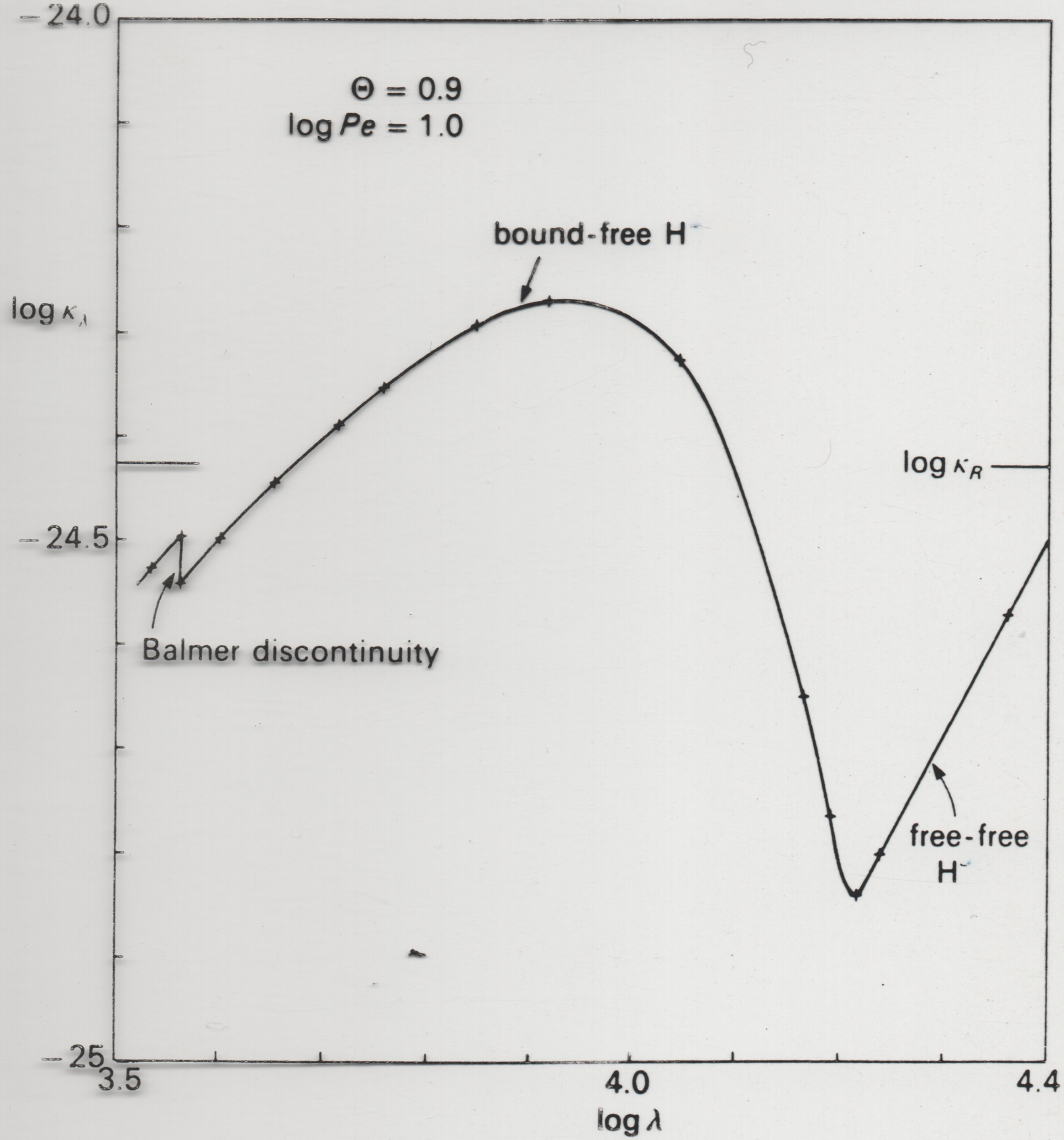


Fig. 7.5. The continuous absorption coefficient per heavy particle is shown for $\Theta = 0.9$, which means $T = 5600$, and $\log P_e = 1.0$. The contributions from the bound-free and free-free continua of H^- are dominant. The small contribution from the Balmer continuum of hydrogen is visible at $\log \lambda = 3.562$. $\bar{\kappa}_R$ is the Rosseland mean absorption coefficient; see section 8.4. (from Bohn-Vitense 1989)

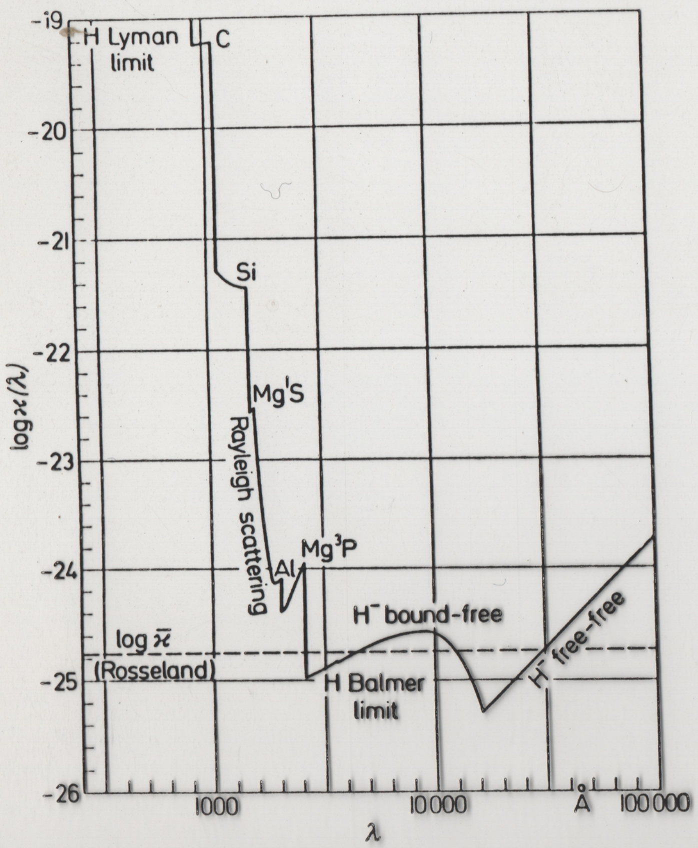


Fig. 7.8. The wavelength dependence of the continuous absorption coefficient per particle is shown for $T_{eff} = 5040$ K ($\Theta = 1.0$) and $\log P_e = 0.5$.

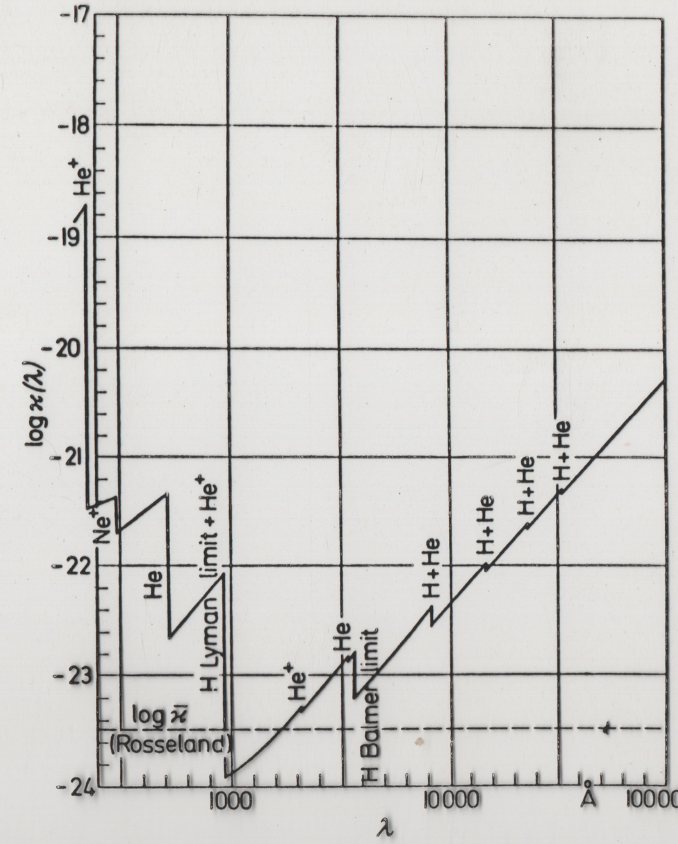
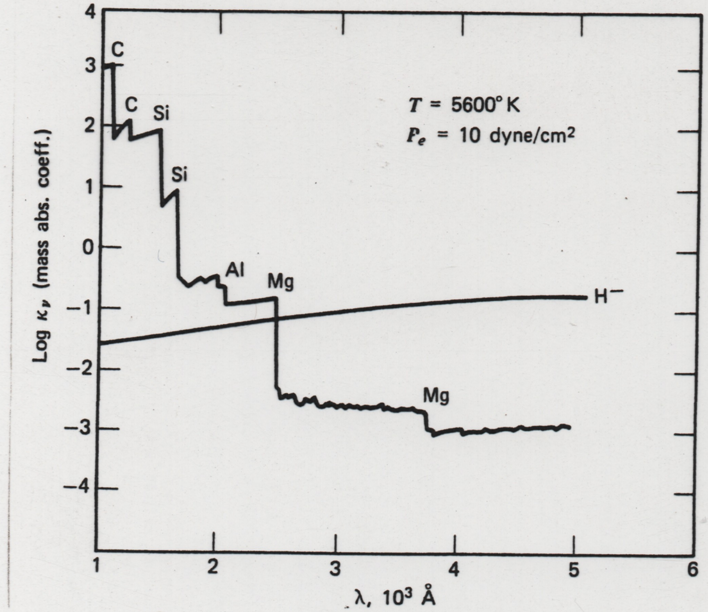
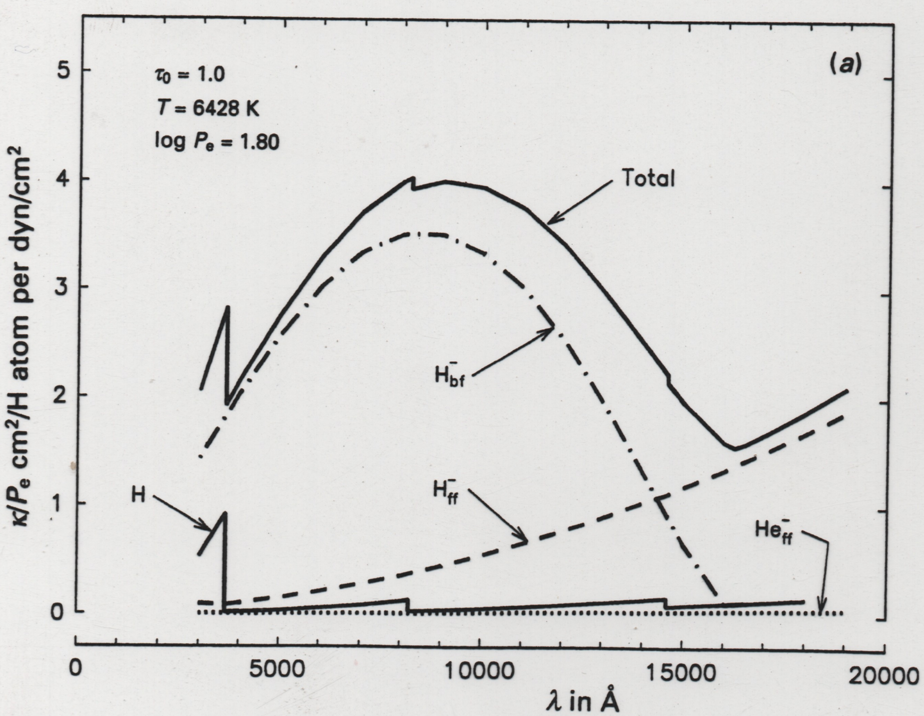


Fig. 7.9. The continuous absorption coefficient per particle is shown as a function of wavelength for a temperature of 28 300 K and $\log P_e = 3.5$ as appropriate for a main sequence B0 star. (From Unsöld, 1977, p. 159.)

(from Bohn-Vitense 1989)





(from Bohn-Vitense 1989)

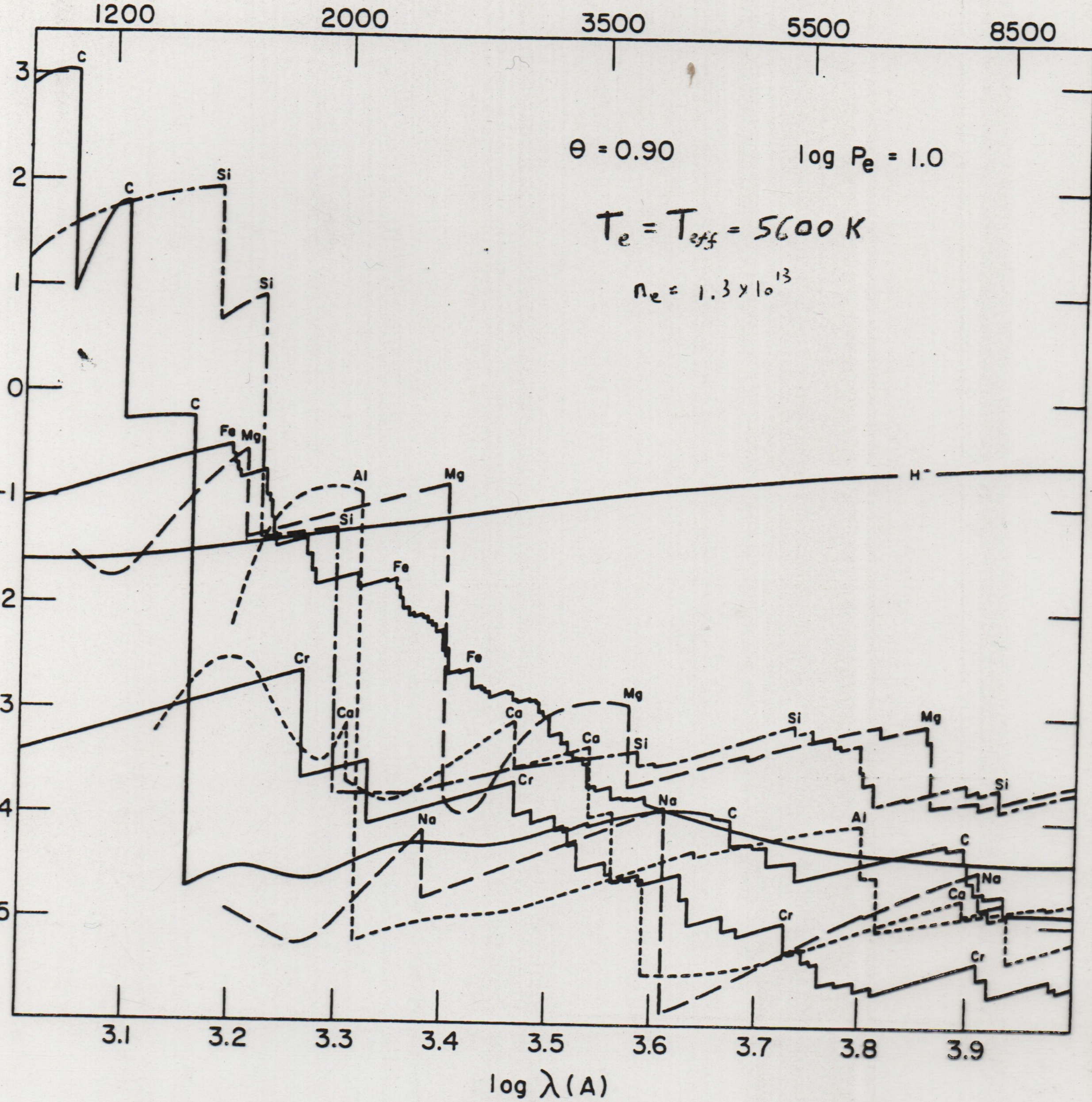
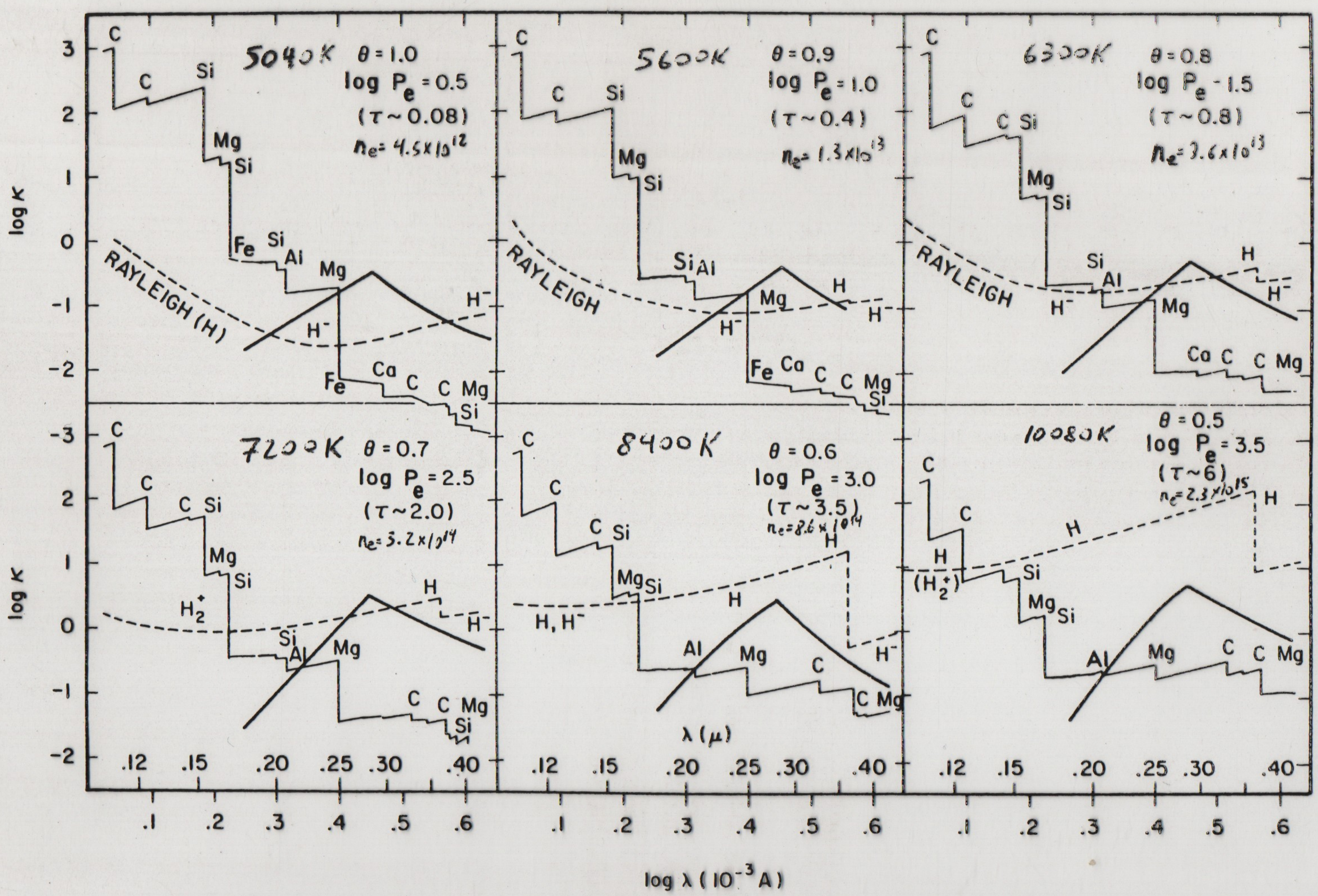


Figure 5. Logarithms of mass absorption coefficients for the individual metals for a solar abundance (Goldberg et al., 1960). The conditions, $\theta = 0.9$ and $\log P_e = 1.0$, are chosen to correspond roughly to $\tau_{5000} \sim 0.5$ for a solar-type star. The individual absorption peaks are labeled to indicate the various metals, and the absorption due to H^- is included for comparison.

(from Matsushima 1973)



. Comparisons of the variations of the mass absorption coefficients with wavelength and depth for the unknown source assumed (heaviest lines), for the metals (lighter solid lines), and for H, H^-, and H_2^+ combined (dotted lines). The important peaks are labeled to indicate the metal responsible for that discontinuity, and the dominant state of hydrogen is marked on each portion of the dotted lines. The value of τ indicates the optical depth at λ 5000 of the layer roughly corresponding to each selected pair of θ and log P_e in the solar atmosphere.

(from Matsushima 1973)