Continuum Absorption

Gray Chapter 8

Equation of Radiative Transfer

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So far we have been talking about emission(-like) processes such as Blackbody radiation, Bremstrahlung, Synchrotron Radition, and Inverse Compton Scattering.

But now we'll switch over to look at absorption processes like bound-free, free-free, scattering, and dust.

The Absorption Coefficient

The total absorption coefficient is given by the summation of the absorption over many different processes.

$$\kappa_\nu = \sum \kappa_\nu$$

These processes can be broken down into two types:

✦bound-free (ie. freeing a bound electron in Hydrogen)

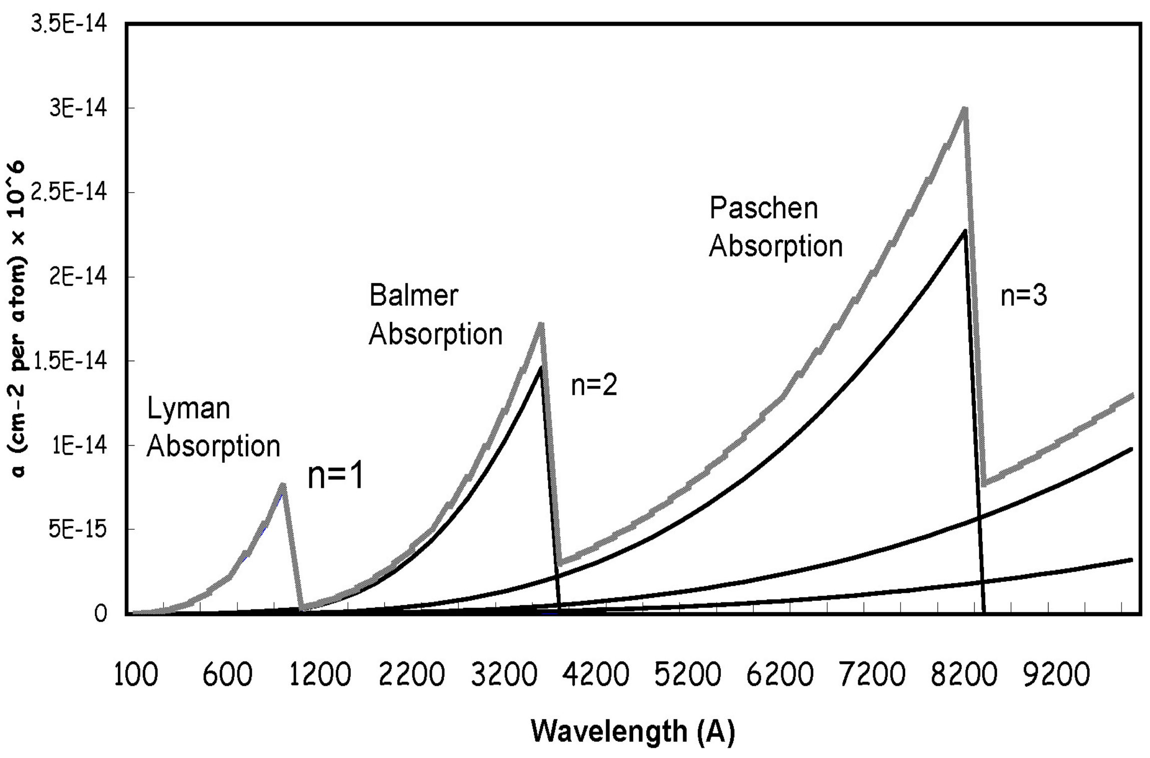
✦free-free (ie. Bremstrahlung)

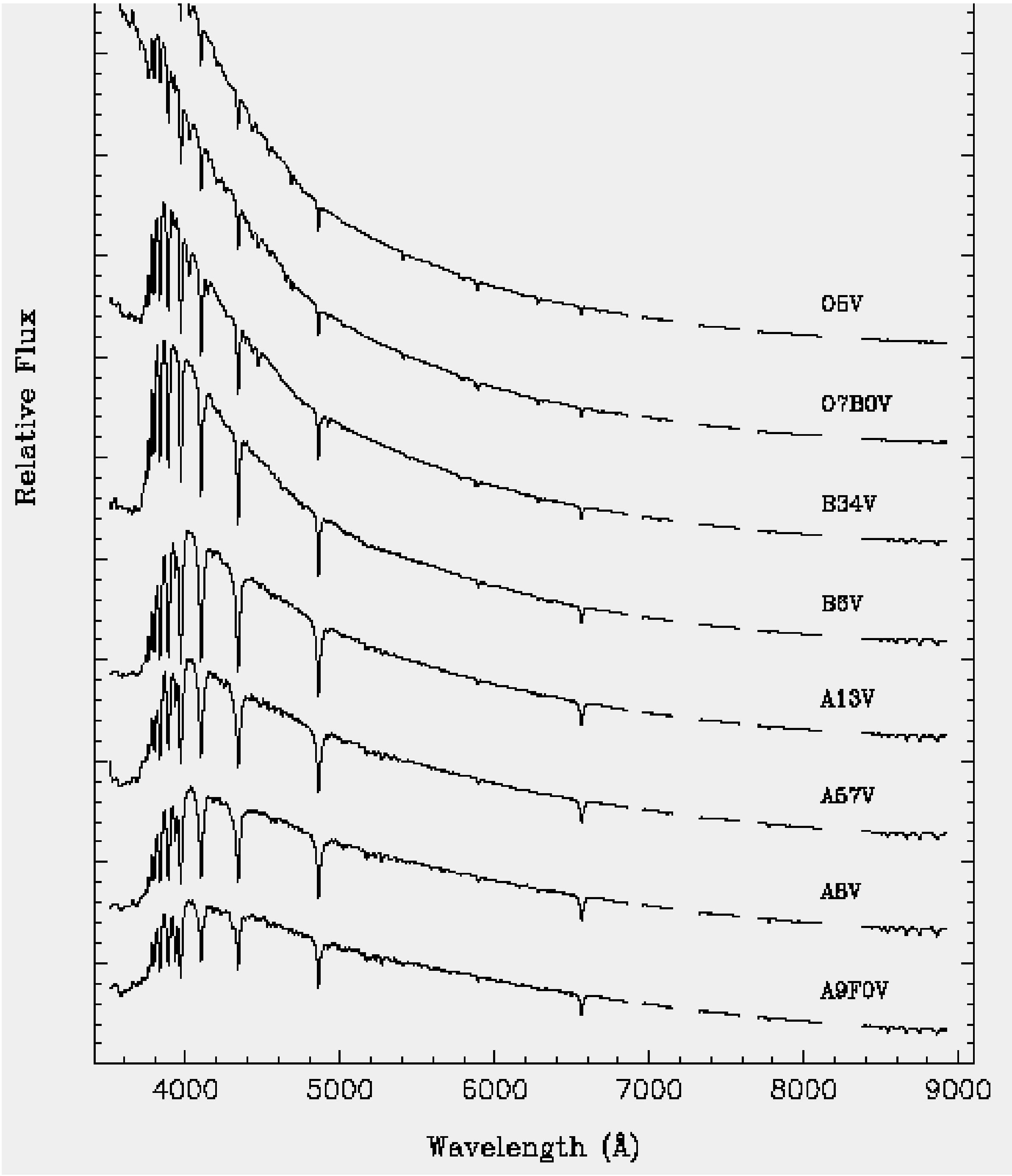
Line absorption is typically handled separately although may appear as continuous for closely overlapping lines.

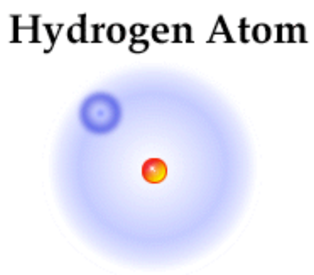
NB: The values for the absorption coefficient reported in Gray are in terms of cm^2/particle and need to be converted to cm^2/g in order to be used in the radiative transfer equation

Bound-Free Absorption

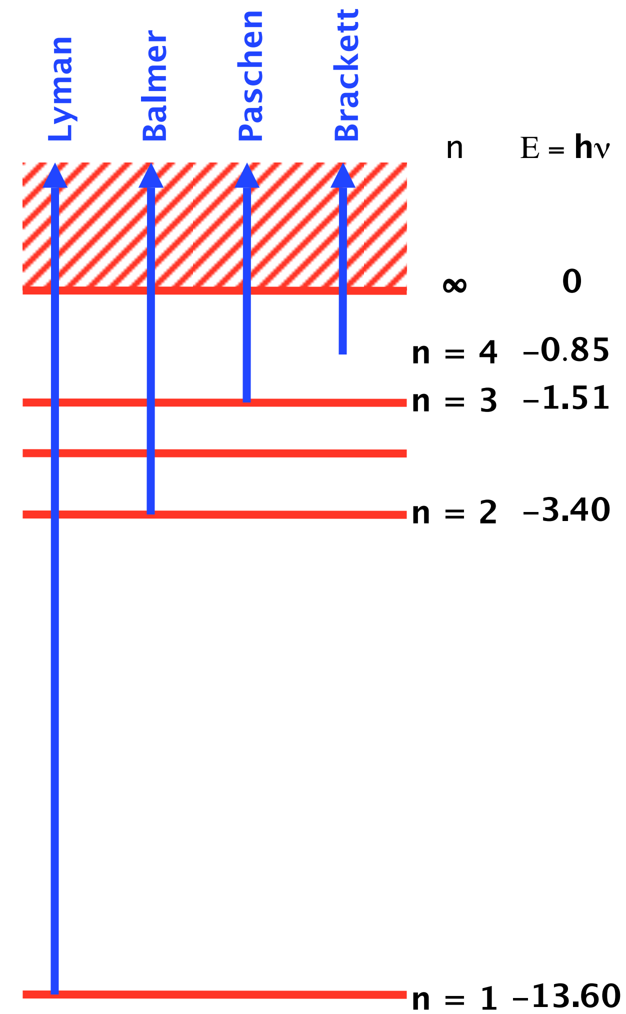
Hydrogen dominates the continuous absorptive processes due to being the most abundant element. The most common process of absorption at optical wavelengths is the bound-free process: a photon ionizing a neutral hydrogen atom.







The Hydrogen Atom



The simple, Bohr model of the hydrogen atom is sufficient to demonstrate bound-free interactions. In this model, the electron orbits the nucleus at different levels. The energy required to release an electron from a given orbit is given by:

$$E_n = -\frac{hRc}{n^2} = -\frac{13.6eV}{n^2}$$

where R is the Rydberg constant and is equal to 1.0968×10^5 cm^{-1}. The table on the right gives the wavelength for a photon with sufficient energy to ionize a hydrogen atom in different states of excitation.

n	λ (Å)	Series name
1	912	Lyman
2	3,647	Balmer
3	8,206	Paschen
4	14,588	Brackett
5	22,790	Pfund

Absorption Coefficient

For photons with energy greater than E_n, The atomic absorption coefficient for bound free absorption is:

$$\alpha_n = \frac{32\pi^2 e^6}{3^{3/2} h^3} \frac{R g_n^{bf}}{n^5 \nu^3} = \frac{\alpha_o g_n^{bf} \lambda^3}{n^5}$$

The absorption coefficient for bound-free absorption in cm2/atom is then:

$$\kappa_\nu(H_{bf}) = \sum_{n_o}^{\infty} \frac{\alpha_n N_n}{N} = \alpha_o \sum_{n_o}^{\infty} \frac{\lambda^3}{n^3} g_n^{bf} \exp - \frac{h\nu}{kT}$$

where

$$\frac{N_n}{N} = \frac{2n^2}{u_o(T)} \exp - \frac{h\nu}{kT}$$

Bound-Free Absorption

$$\alpha_n = \frac{32\pi^2 e^6}{3^{3/2}h^3}\frac{Rg_n^{bf}}{n^5\nu^3} = \frac{\alpha_o g_n^{bf}\lambda^3}{n^5}$$

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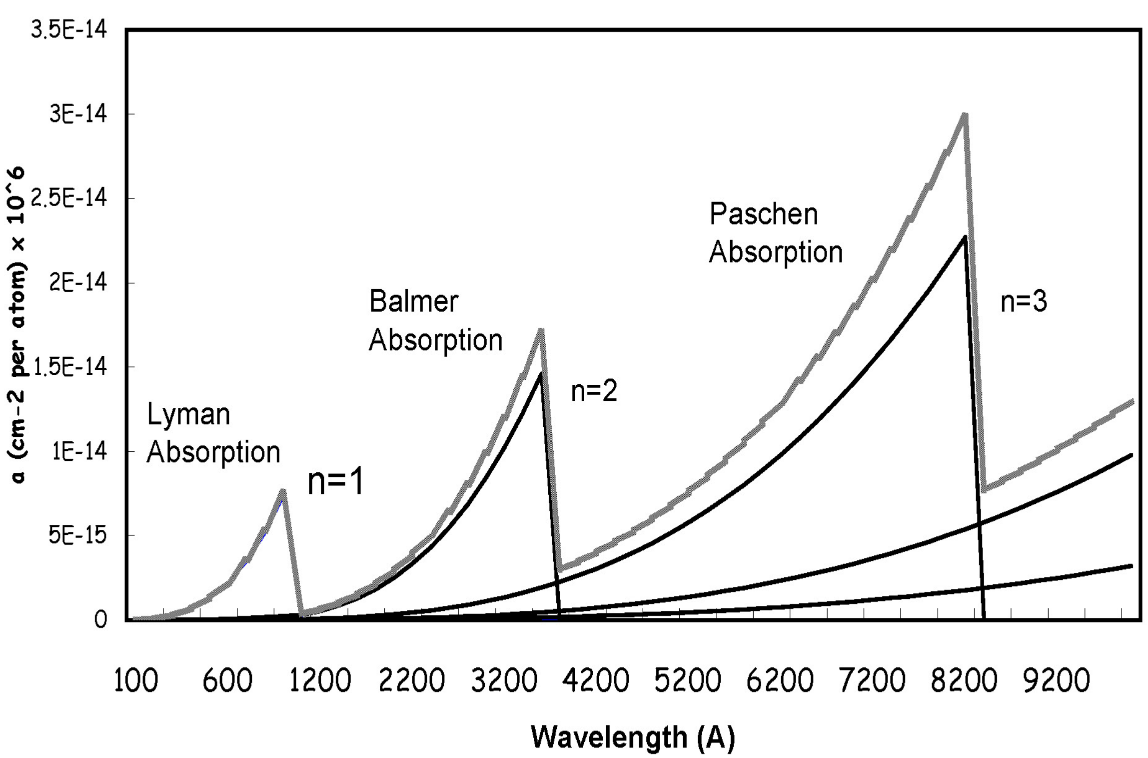
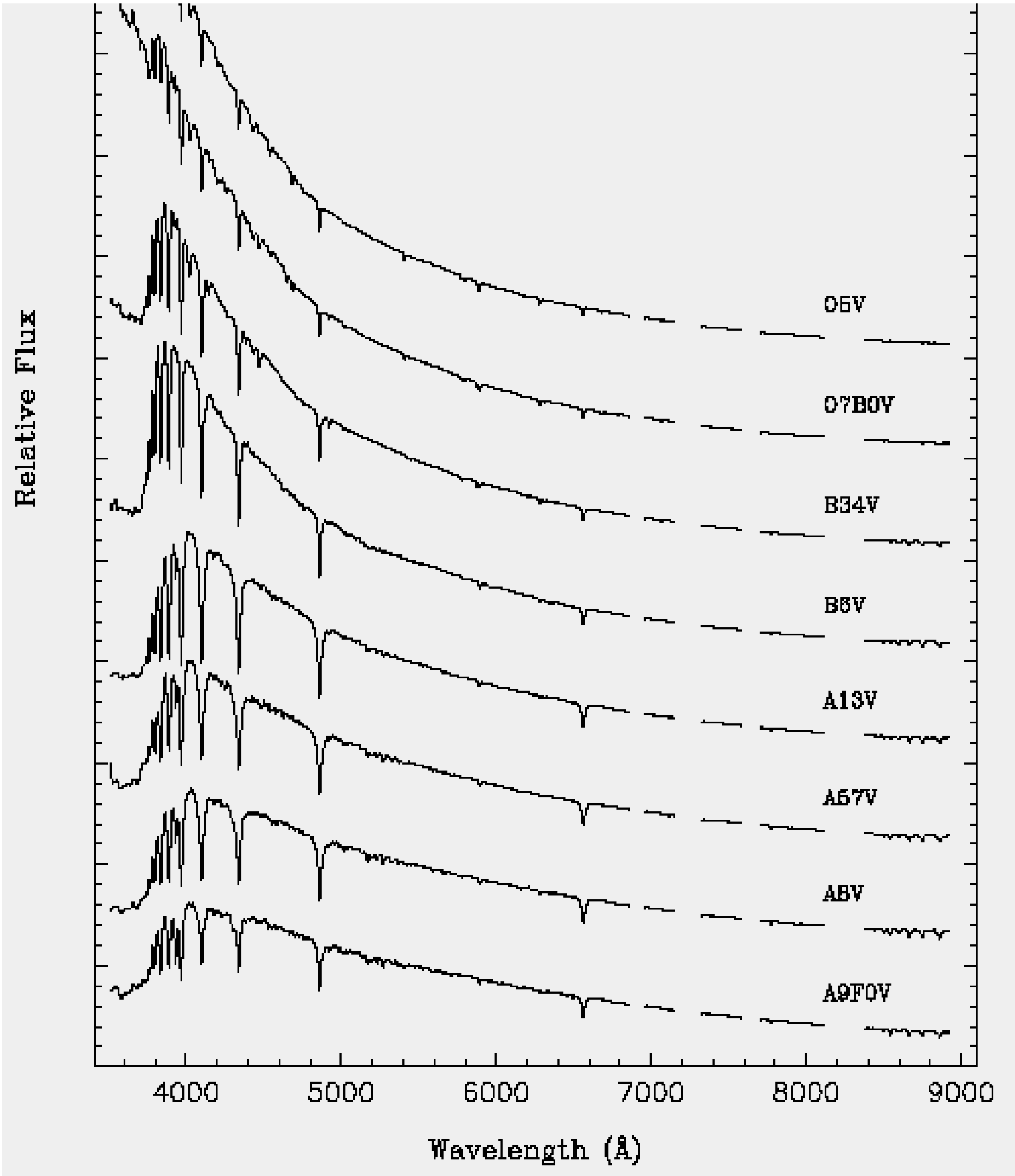
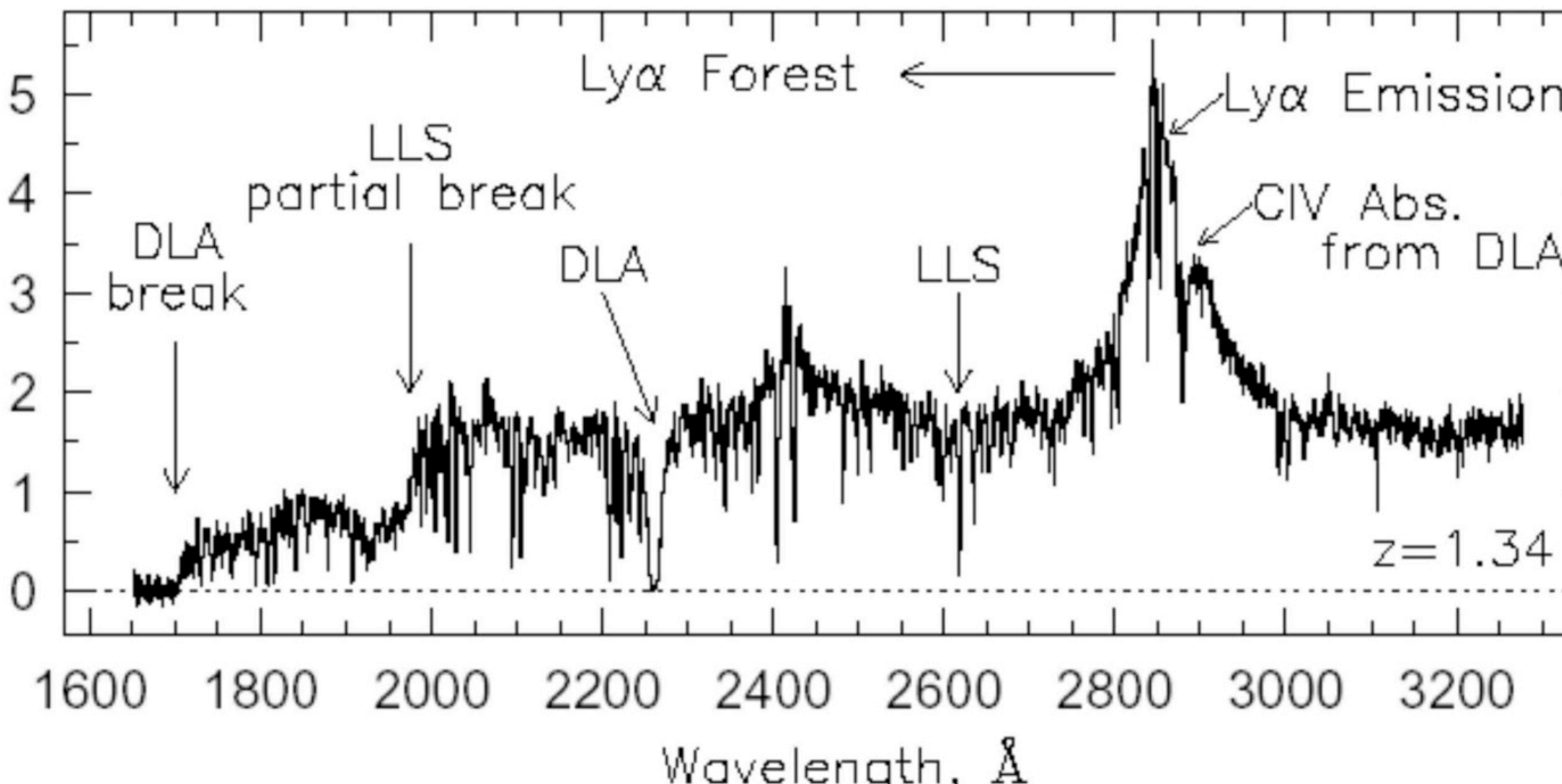




Absorption at High Redshift and re-ionization



Free-Free Absorption

Free-free absorption has already been considered in the last lecture, but here, we state it in just terms of the atomic absorption coefficient:

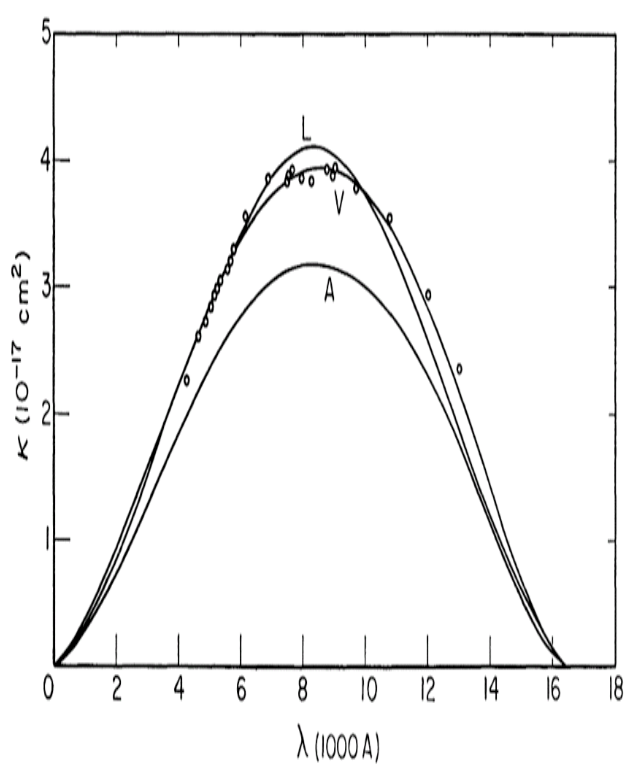
$$\alpha_{ff} = \frac{2h^2e^2R}{3^{3/2}\pi m^3}(\frac{2m}{\pi kT})^{1/2}\frac{1}{\nu^3}$$

So the absorption per atom is:

$$\kappa_\nu(H_{ff}) = \alpha_{ff}g_\nu^{ff}\frac{N_iN_e}{N} = \alpha_{ff}g_\nu^{ff}\frac{(2\pi mkT)^{3/2}}{h^3}\exp\frac{-h\nu}{kT}$$

H^- ion absorption

The hydrogen atom can also hold an extra electron in its shells and be negatively charged. This electron can be ionized by a photon of 0.754 eV or λ = 16,444 Å. In addition to a bound-free effect, there is also an effect of the free-free absorption as well which is important in the infrared bands. H^- absorption becomes important in cool stars and also has affects on the CMB.



S. Geltman 1962

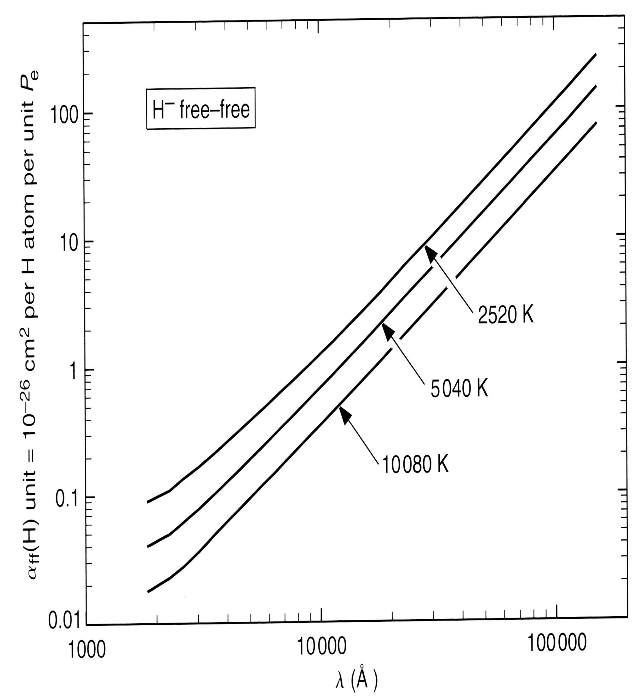
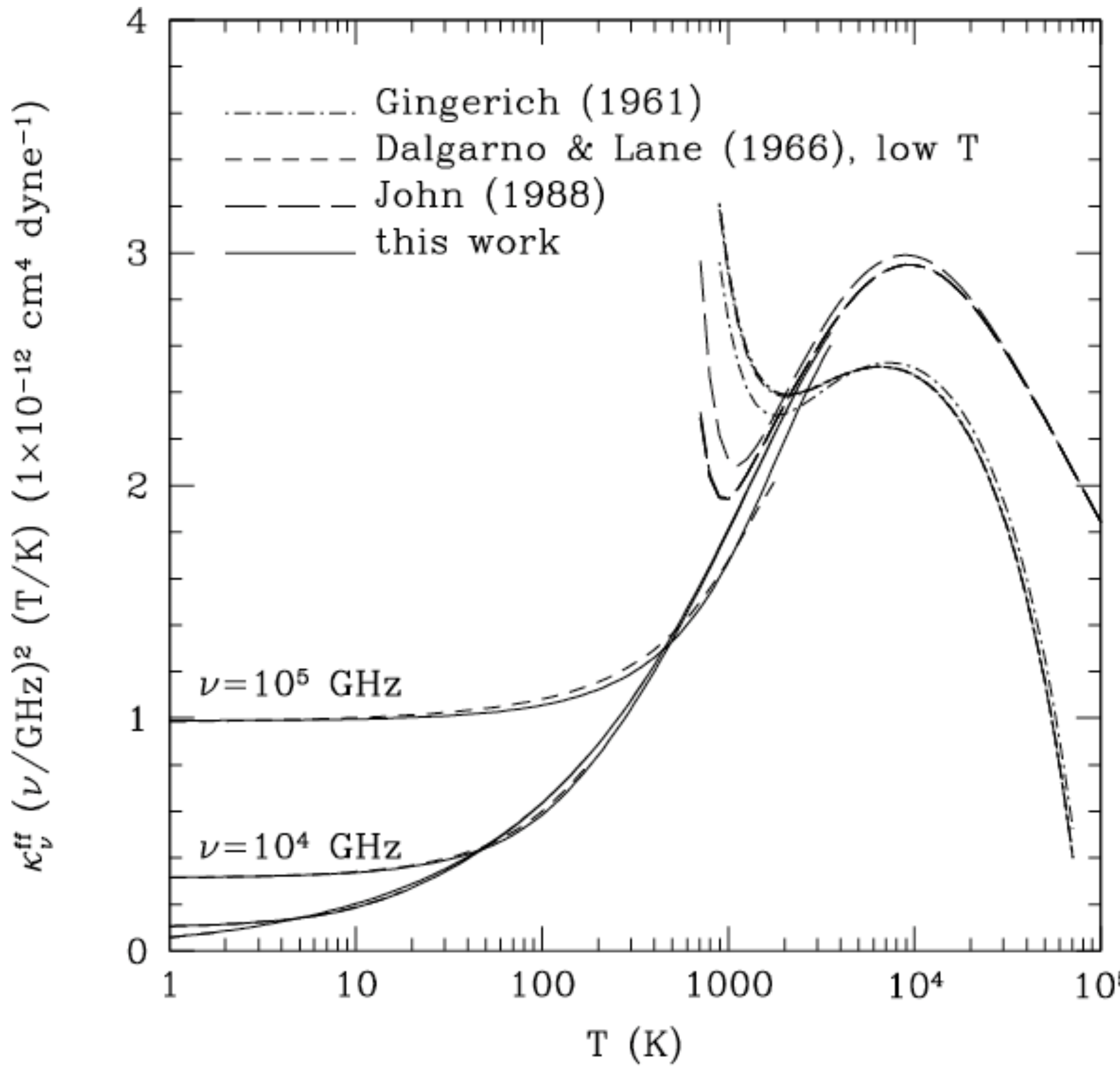


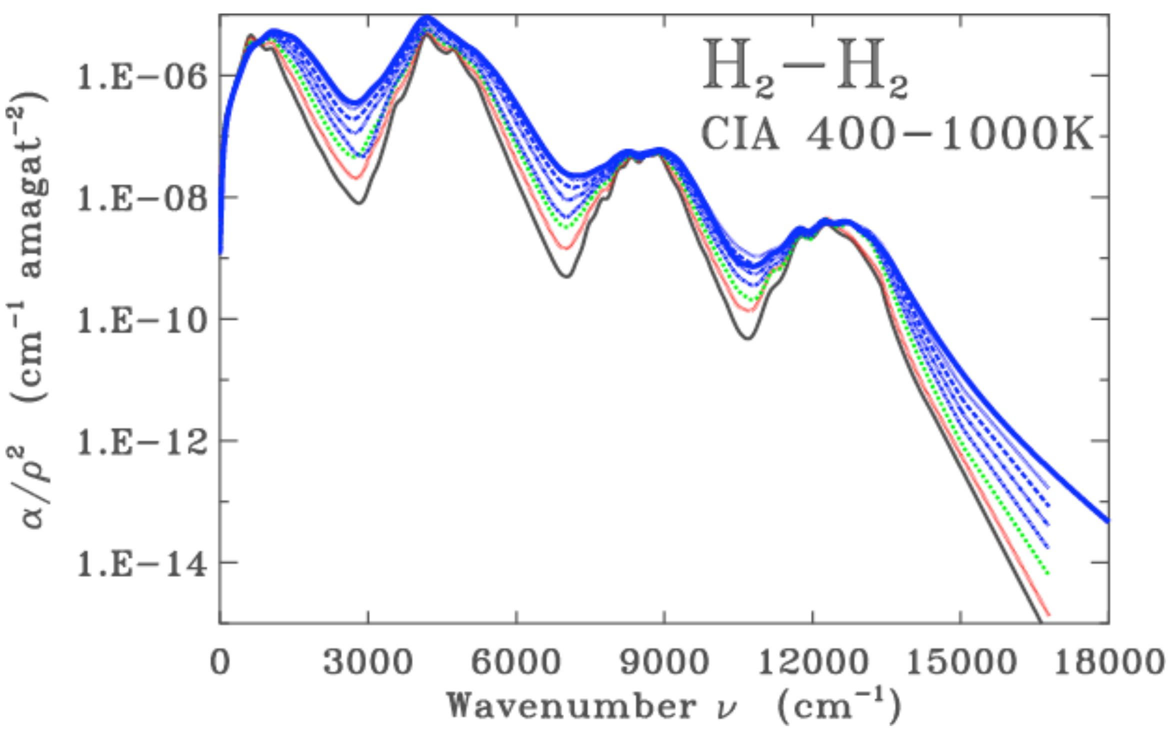
Fig. 8.4. The free–free absorption coefficient of the negative hydrogen ion increases rapidly with wavelength. The stimulated emission factor is included here.



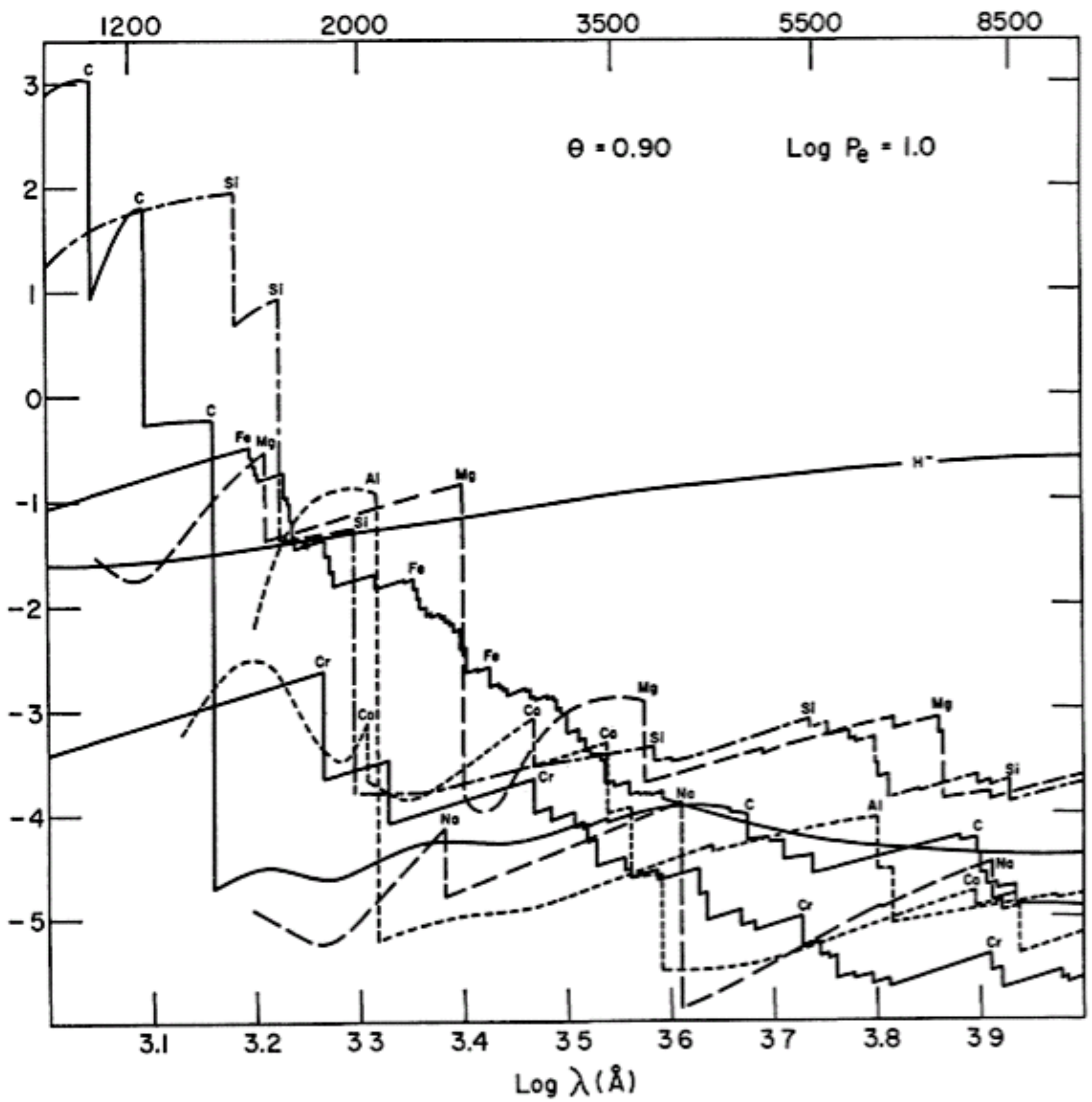
Schleicher et al 2008

Molecular Hydrogen

Molecular hydrogen can be very important in cool stars and in the infrared. Neutral H2 has no dipole moment, but absorption processes become important for H2+ or H2- and can be important in both bound free and free-free emission.



Heavy Ions



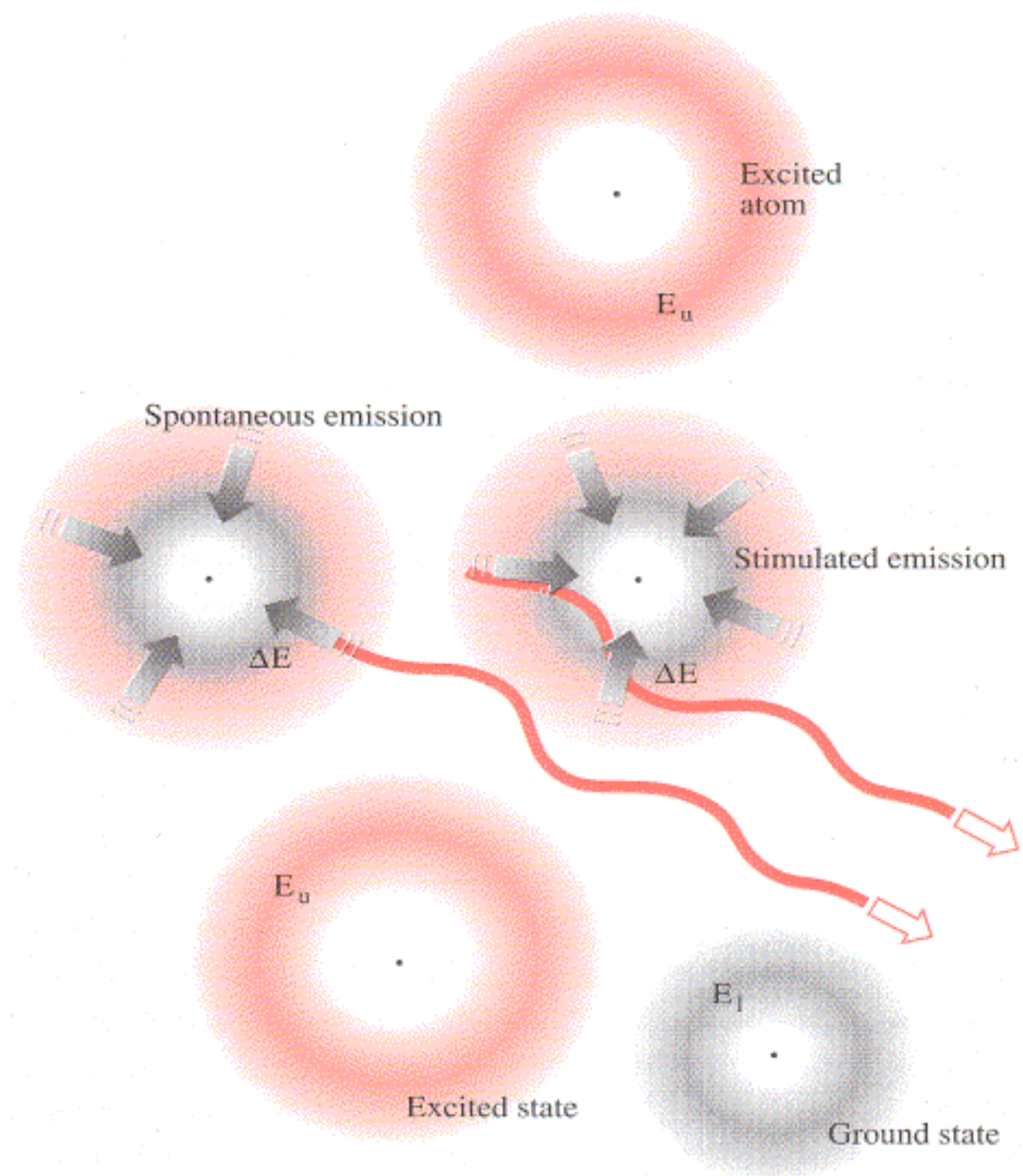
Travis and Matsushima, 1968

Bound-free and free-free He absorption can become important in the hotter stars. Elements such as C, Si, Al, Mg and Fe produce bound-free opacity in the UV. Molecules become more dominant in very late-type stars.

The plot here illustrates a number of atomic cross-section in the UV and optical or a solar-like star. Generally, these are dominated by H⁻ except in the UV, where e.g. C, Si and Fe have great importance.

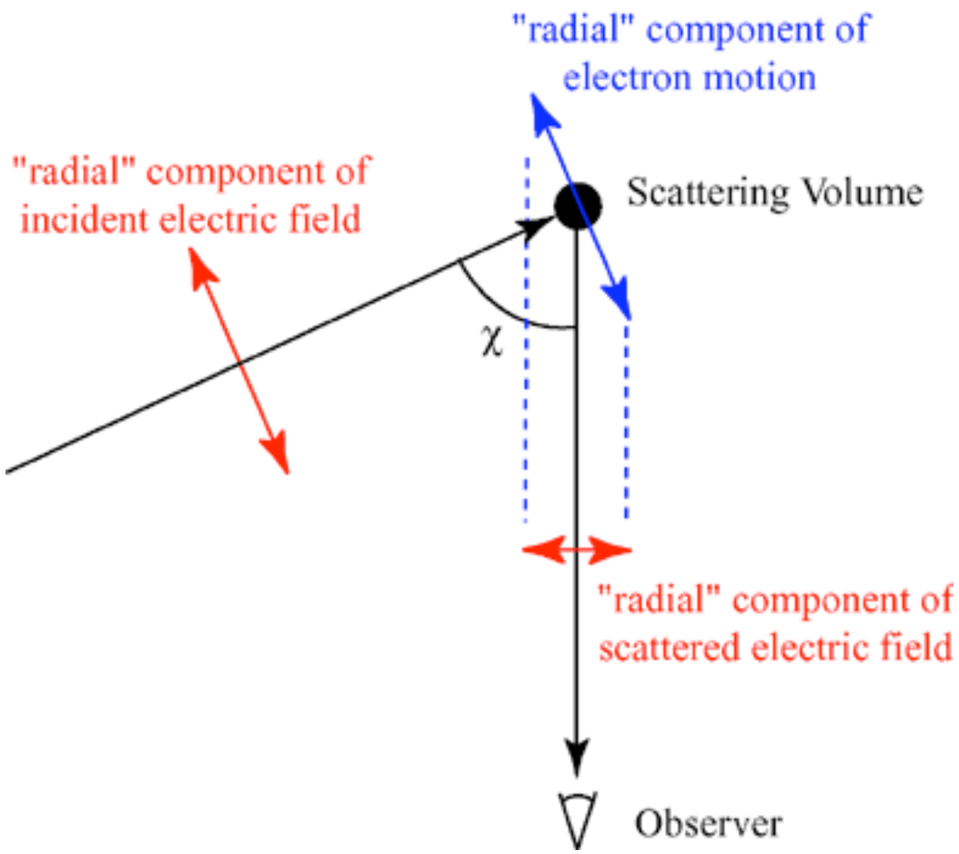
Stimulated Emission

Stimulated emission is the process by which, when perturbed by a photon, matter may lose energy resulting in the creation of another photon. The perturbing photon is not destroyed in the process (cf. absorption), and the second photon is created with the same phase, frequency, polarization, and direction of travel as the original. We will be looking at this in a lot more detail when we look at line emission.



Scattering

Thomson scattering is the scattering of photons by non-relativistic electrons. Because the electron energies are much lower, the change in photon wavelength is negligible. However, this process does contribute to the total absorption coefficient. It plays an important role in polarizing the CMB and can be used to estimate the electron density in the solar corona.



The absorption coefficient for Thomson scattering is:

$\kappa(e) = \sigma_e \, (N_e/N_H)$

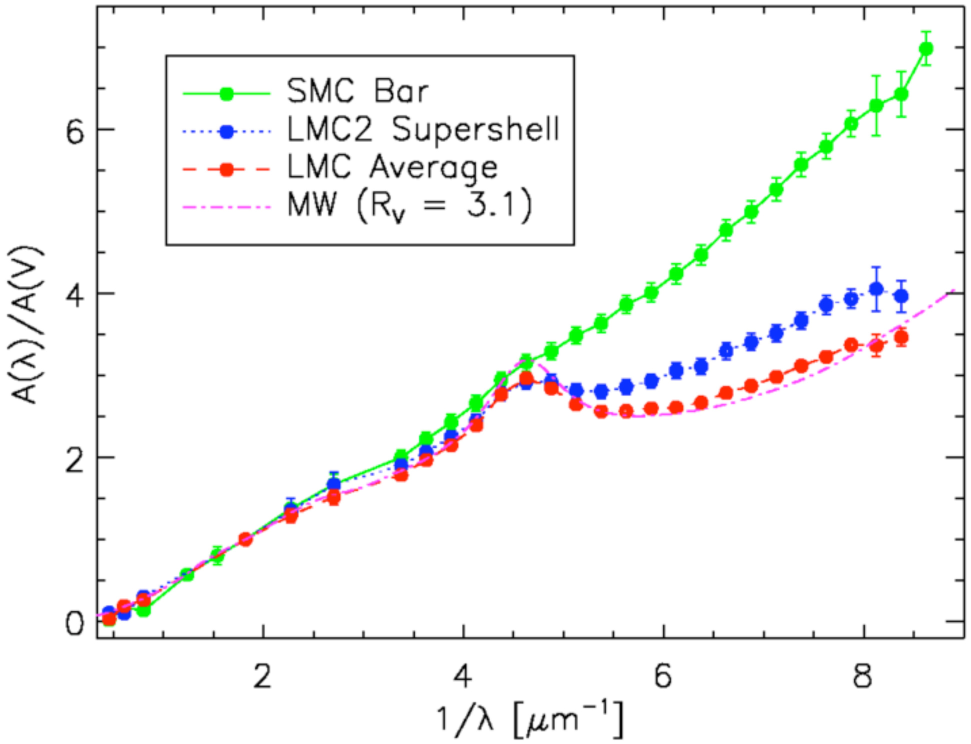
where the Thomson cross section is:

$\sigma_e = 8\pi/3 \, (e^2/mc^2)^2$

$= 6.26 \times 10^{-25}$ cm^2

Dust

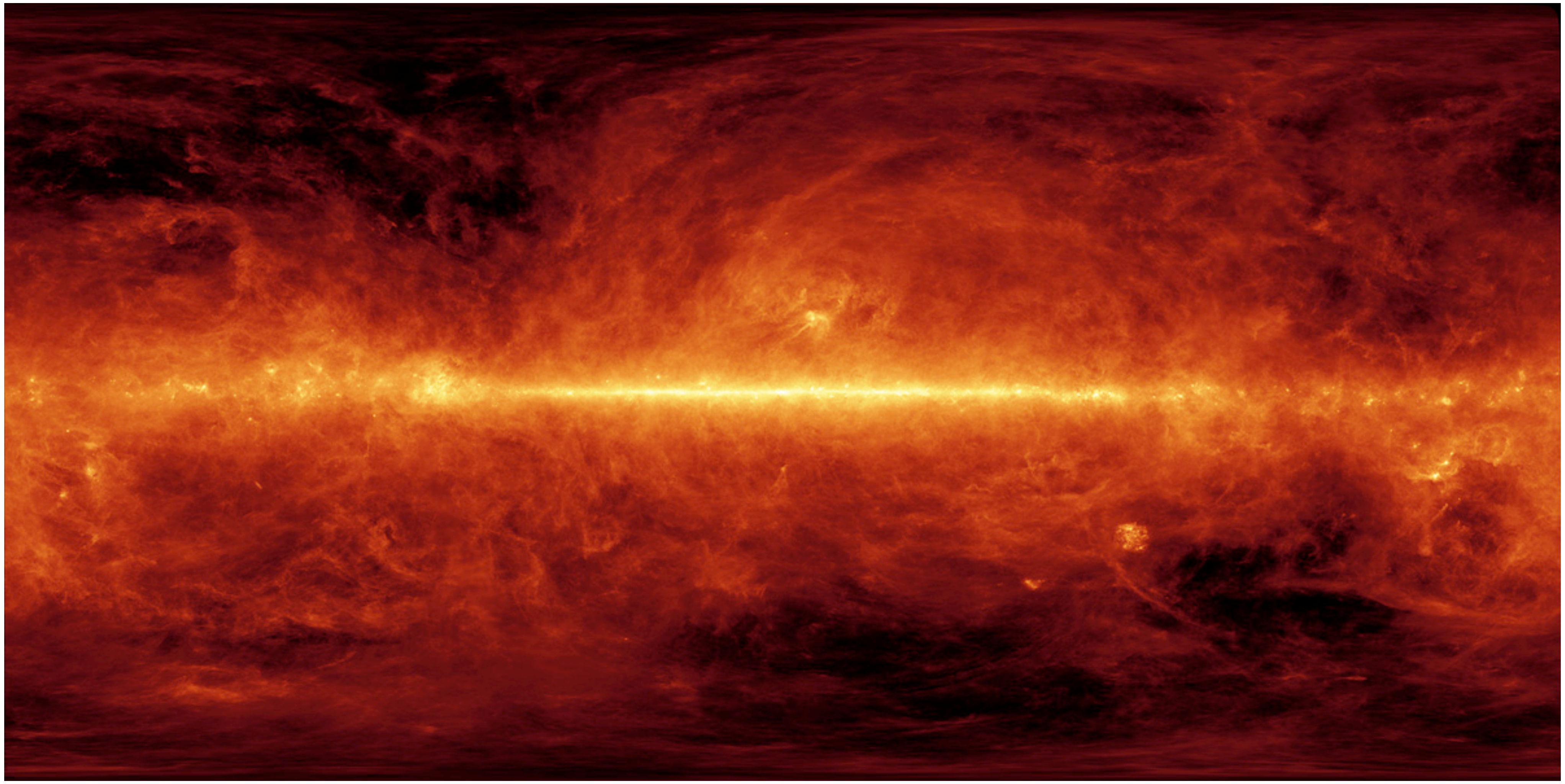
Dust and complex molecules absorb a significant amount of light from any sources. Dust is a very complicated phenomenon that affects almost every aspect of astronomy. The geometry, composition, size, and absorption of dust in different systems including the Milky Way are still not well understood.



Pei et al.1992

Extinction curves for several different systems. Why a bump exists at 2171 A in some systems and not others is not yet well understood although it may relate to the metallicity or star formation rate of a system.

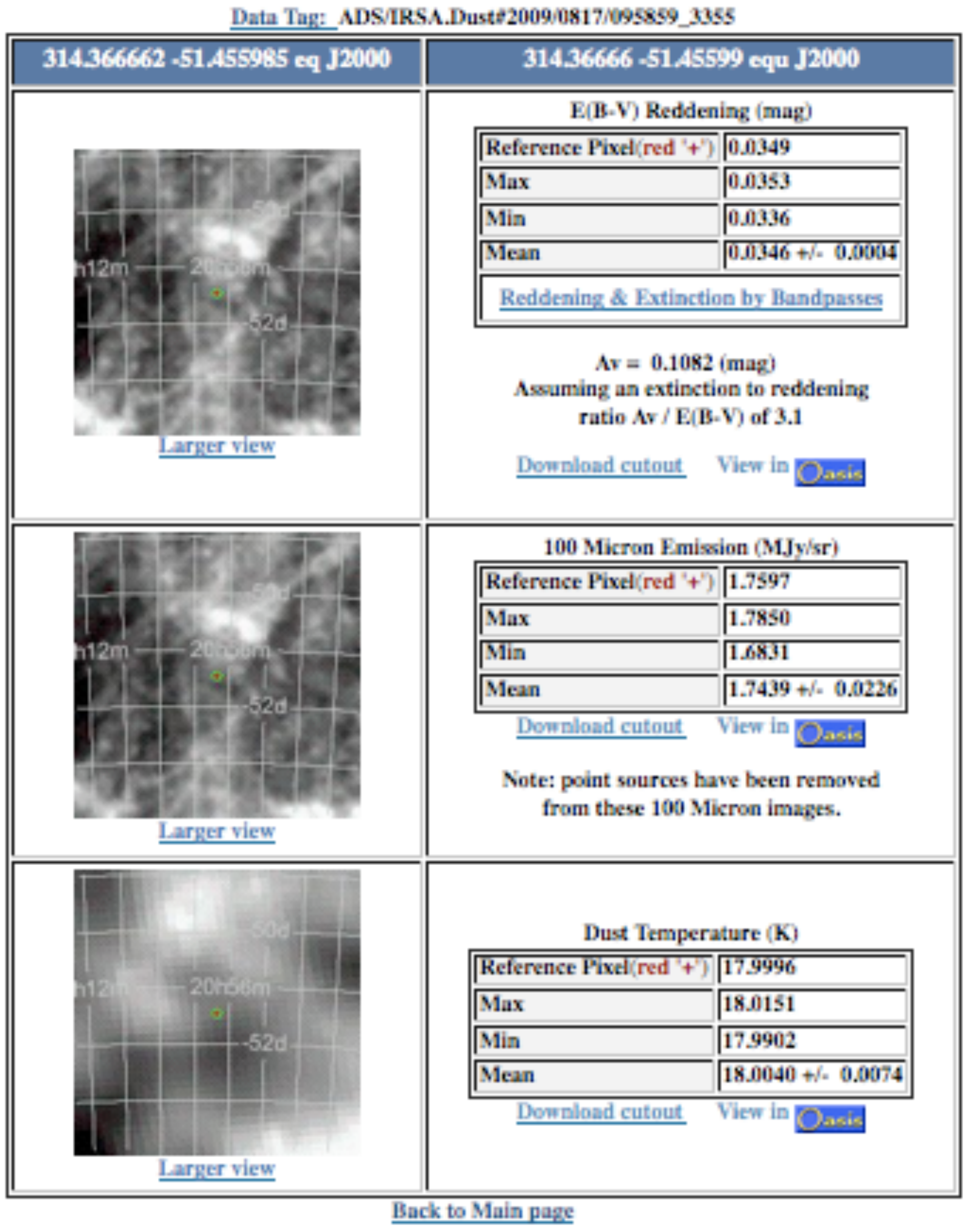
Dust Emission



E(B-V) and Av

The general shape of the UV through near IR extinction curve in our own Galaxy is well characterized by the ratio of the total V-band absorption, AV, to the selective extinction, E(B-V) = AB -AV. The typical value for this ratio, R=AV/E(B-V) = 3.1 for the Milky Way.

Magnitudes typically have to be corrected for galactic extinction. This is done by applying the standard equation for galactic extinction and the value for E(B-V) measured in the direction of the observation. Standard references for this are Burstein and Heiles (1982) and Schlegel, Finkbeiner and Davis (1998). Online tools are available to make the calculation (eg NED), but for a full description of this process, see Cardelli, Clayton, and Mathis (1989)

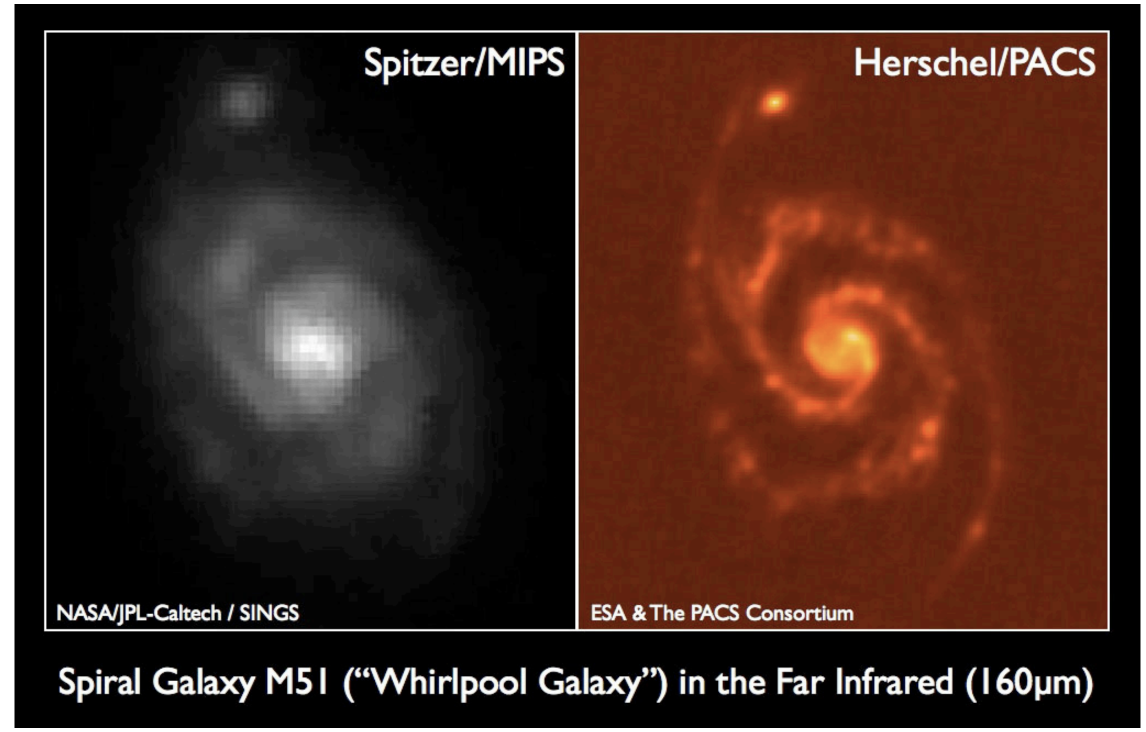


Observing Dust in Galaxies

Dust can dramatically change depending on the geometry of the observation (screen, obscurred, ...)

HST

Howk



And what wavelength the galaxy is observed at. Space infrared telescopes have made significant advances in determining the dust properties of galaxies and much more information is likely to be gained from Herschel

Total Absorption Coefficient

$$\kappa_\nu = \{[\kappa_\nu(H_{bf}) + \kappa_\nu(H_{ff}) + \kappa_\nu(H^-_{bf})](1 - \exp\frac{h\nu}{kT}) + \kappa_\nu(H^-_{ff} + ...\} \times [1 + \frac{N_1}{N_o}]^{-1}$$

$$+ \kappa_\nu(metals) + \kappa_\nu(He^-_{ff})$$

$$+\kappa_\nu(e) + \kappa_\nu(dust) + ...$$

Total Absorption Coefficient

Stimulated Emission

$$\kappa_\nu = \{[\kappa_\nu(H_{bf}) + \kappa_\nu(H_{ff}) + \kappa_\nu(H^-_{bf})](1 - \exp\frac{h\nu}{kT}) + \kappa_\nu(H^-_{ff} + ...\} \times [1 + \frac{N_1}{N_o}]^{-1}$$

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Account for Ionization

$$+ \kappa_\nu(metals) + \kappa_\nu(He^-_{ff})$$

$$+\kappa_\nu(e) + \kappa_\nu(dust) + ...$$

Total Absorption Coefficient

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Hydrogen

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Heavier Elements

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$$+ \boxed{\kappa_\nu(metals) + \kappa_\nu(He^-_{ff})}$$

Heavier Elements

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Scattering

Total Absorption Coefficient

Hydrogen

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Scattering

Dust

Total Absorption Coefficient

Hydrogen

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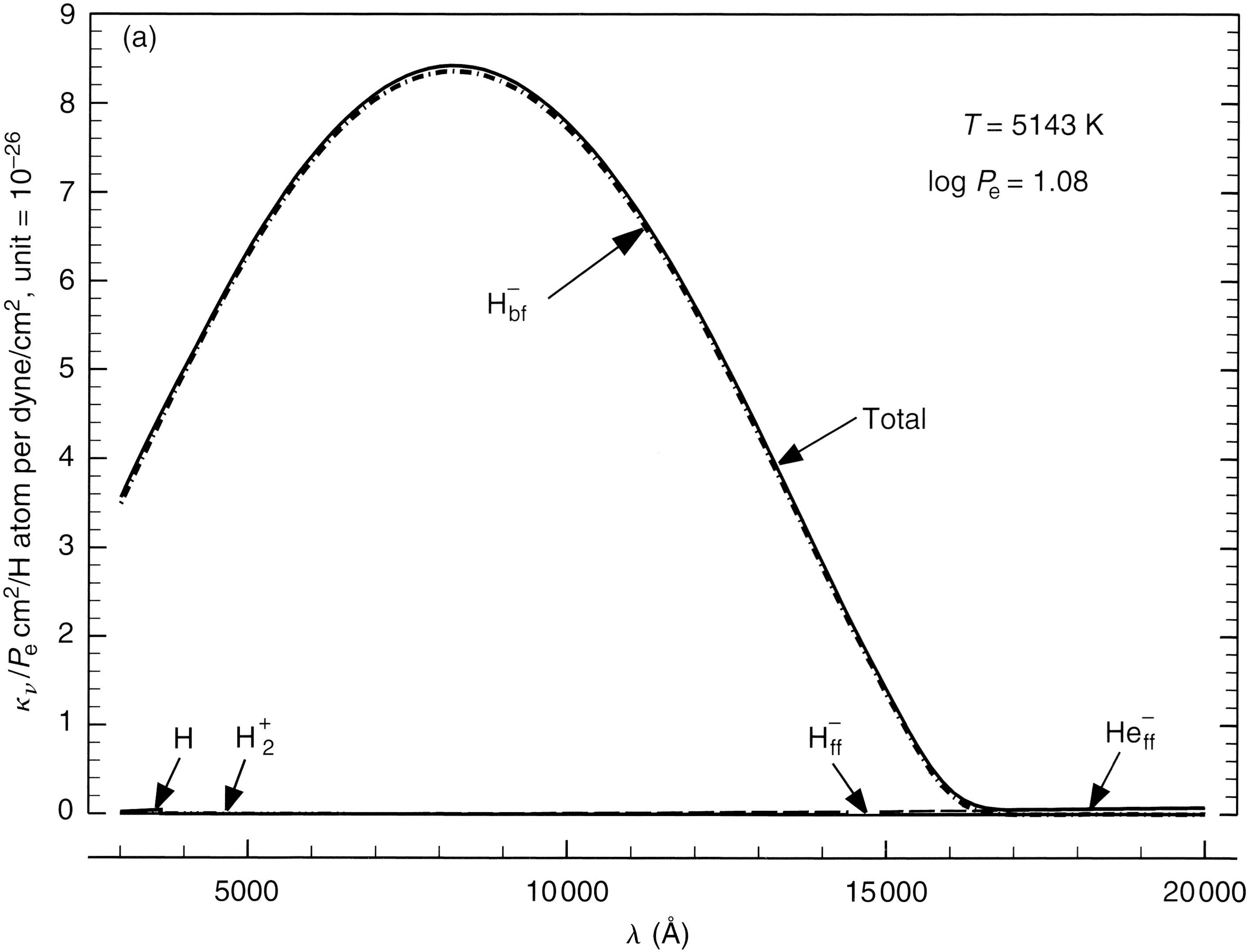
Heavier Elements

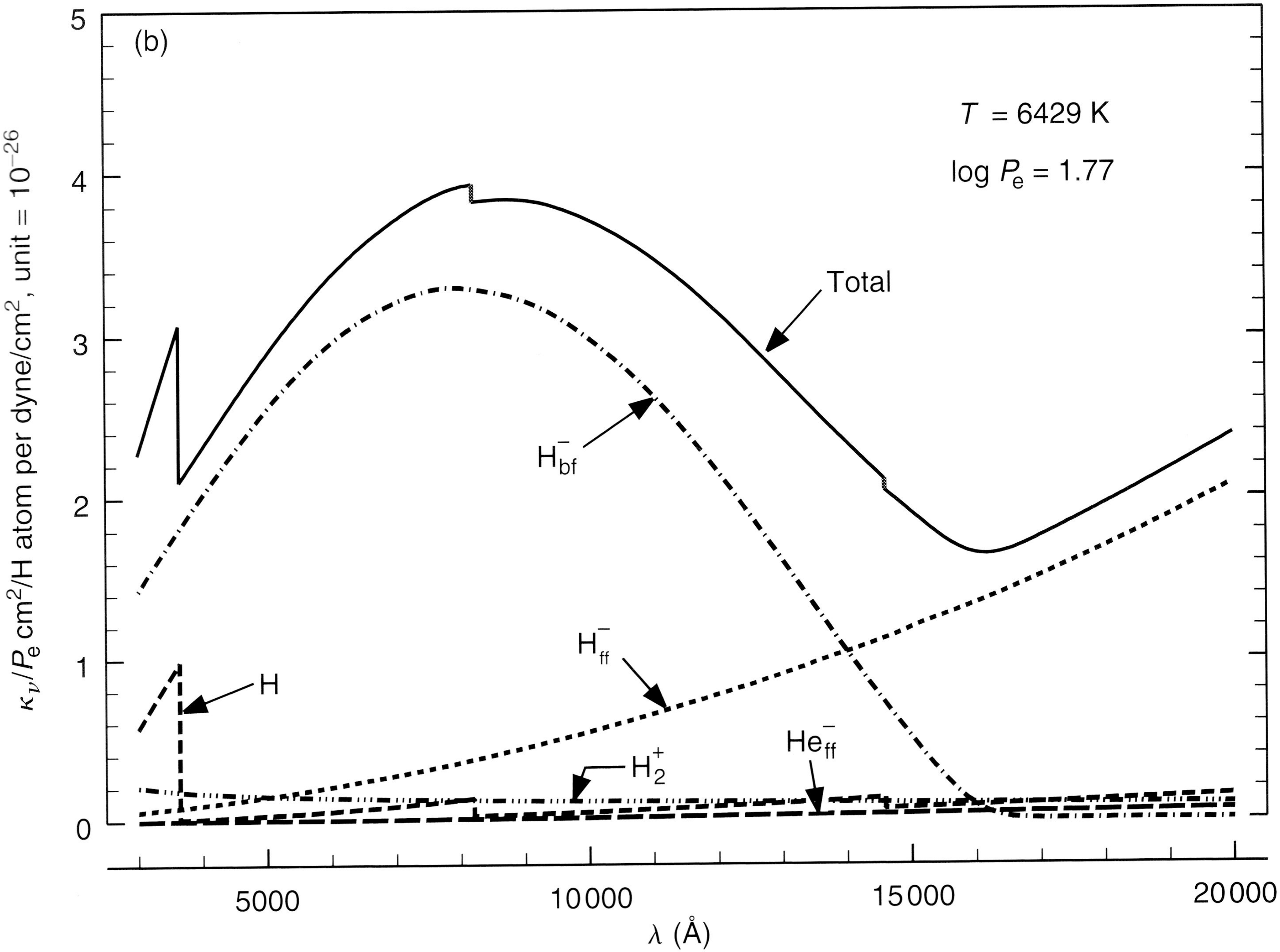
$$+ \boxed{\kappa_\nu(e)} + \boxed{\kappa_\nu(dust)} + ...$$

Scattering Dust

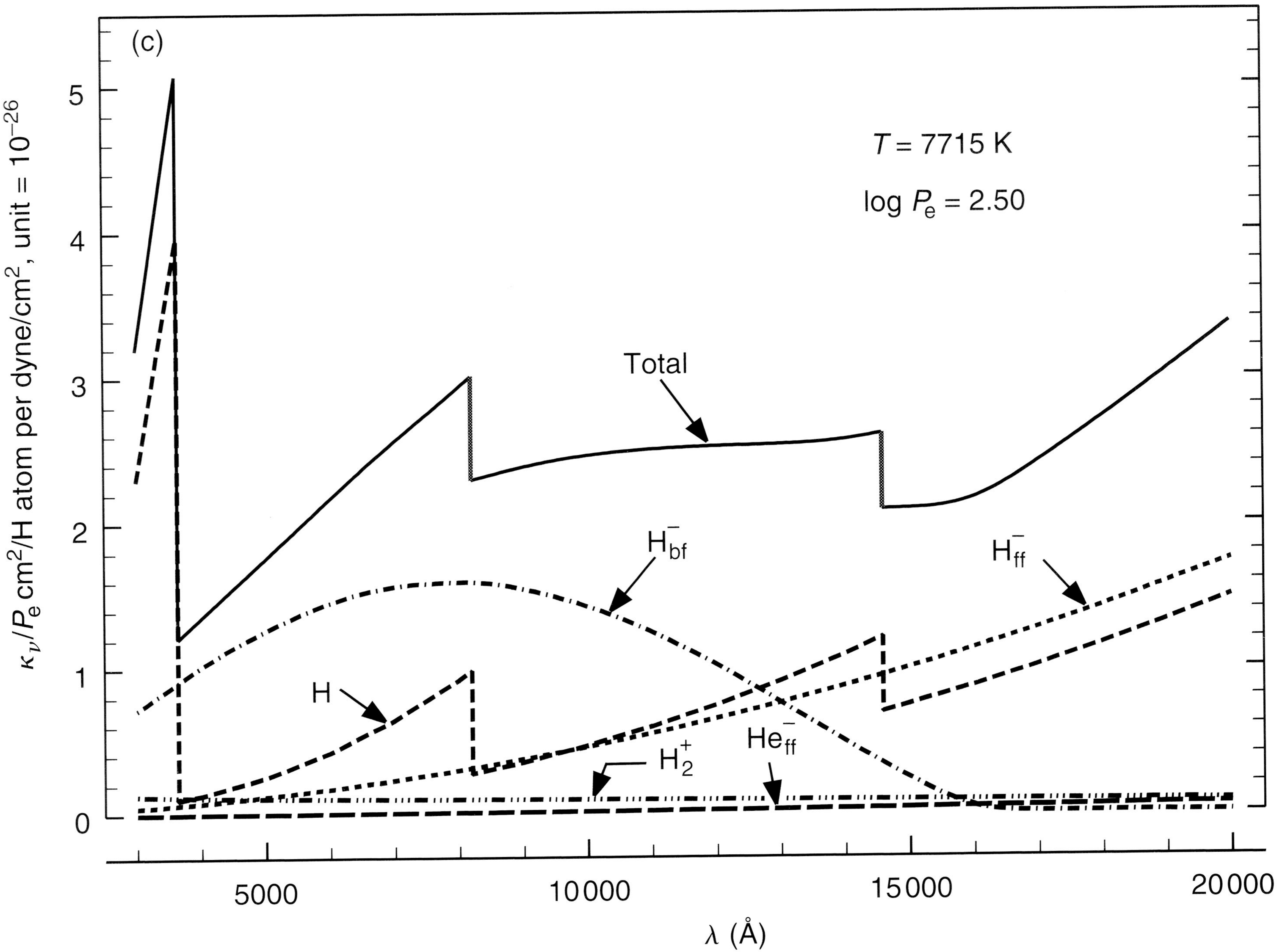
NB: The values for the absorption coefficient reported in Gray are in terms of cm^2/particle and need to be converted to cm^2/g in order to be used in the radiative transfer equation



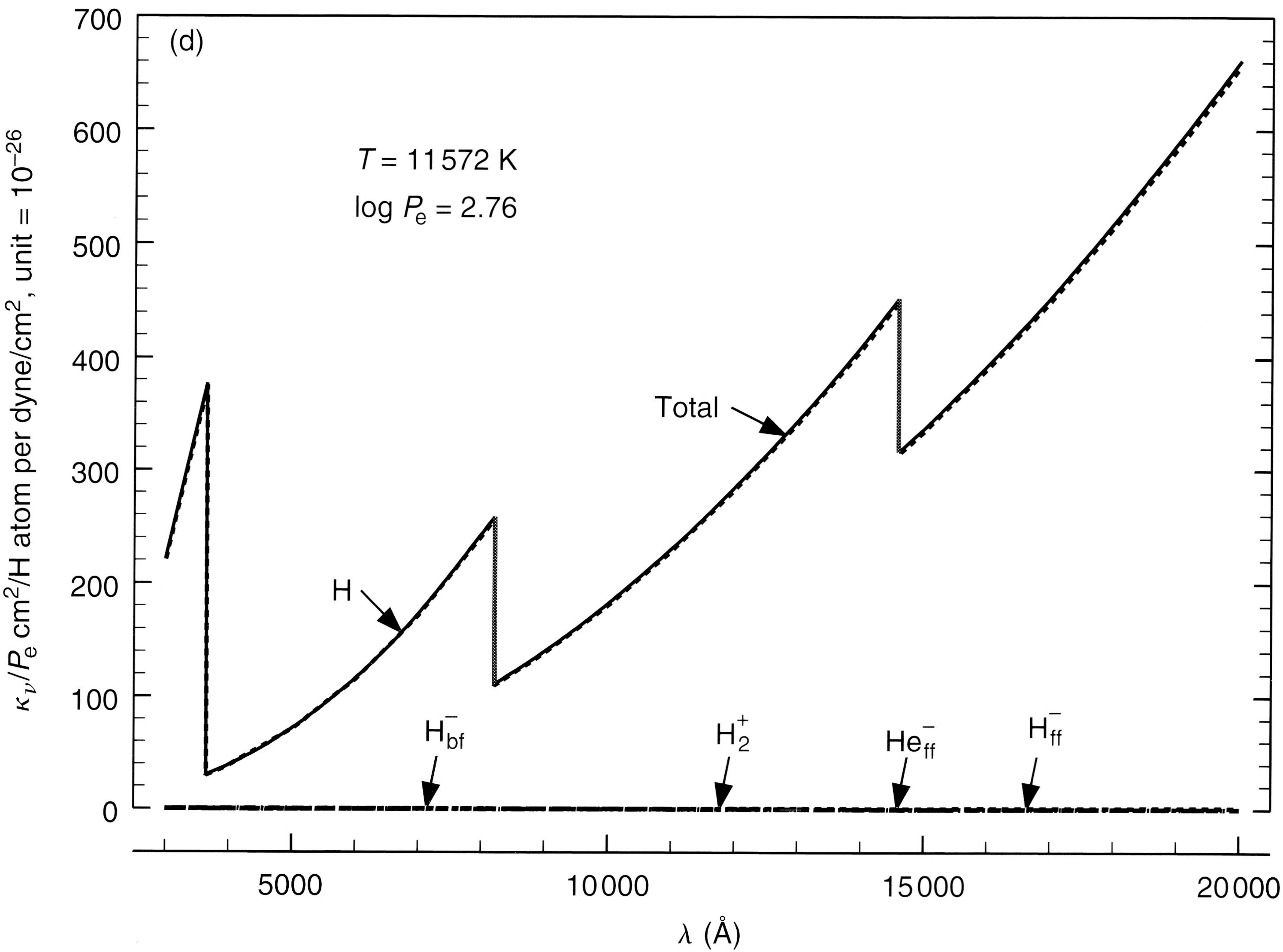
Opacity Sources at 5143K



Opacity at 6429 K

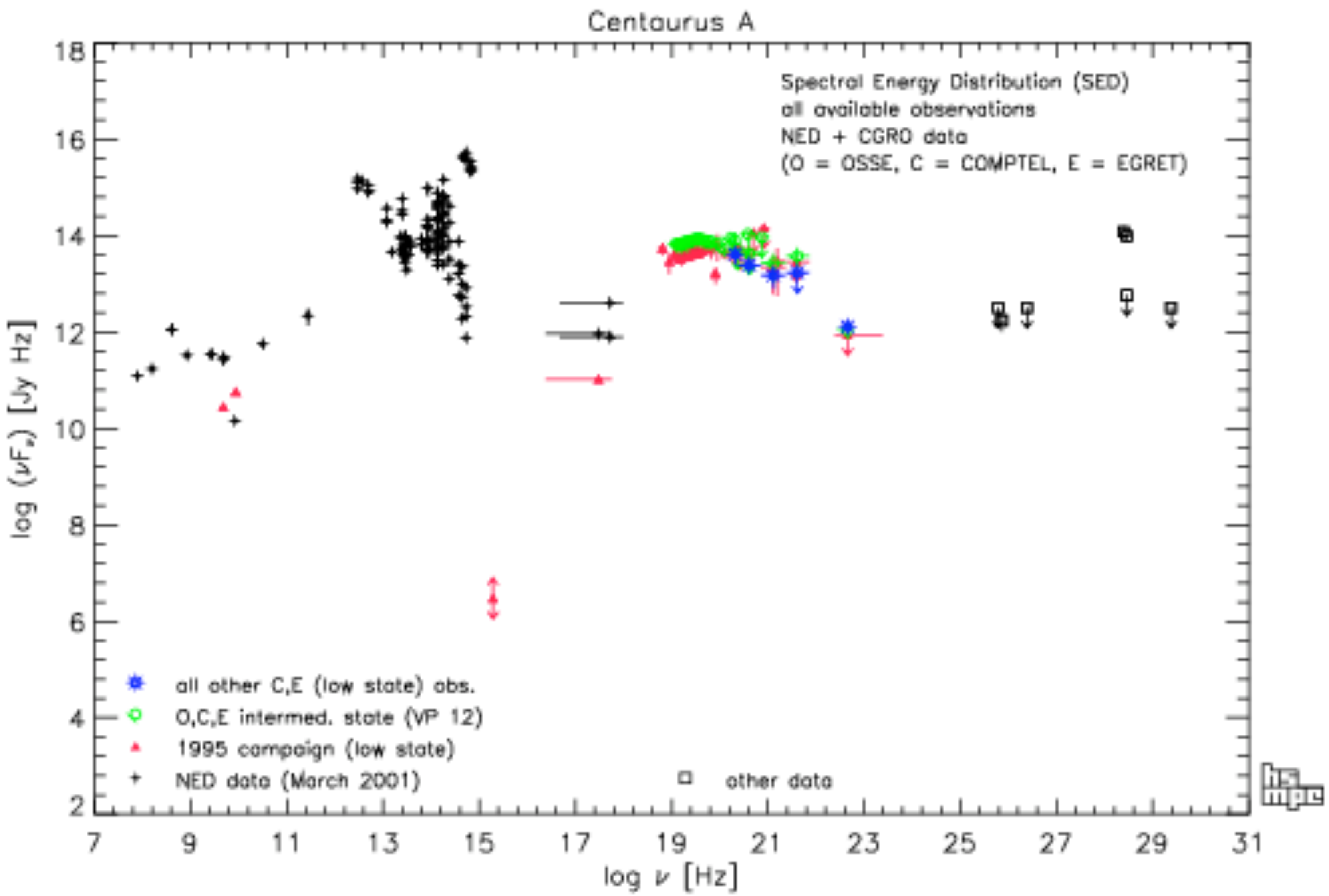


Opacity at 7715 K



Opacity at 11600 K

Centaurus A



Steinle (2006, Chin. J. Astron. Astrophys. 6(Suppl. 1), 106)

Broad-band spectrum of Cen A: Spectral Energy Distribution (SED) νf_ν is flat $\Longrightarrow$ similar energy output at all wavebands!

Shown is a νf_ν-plot, where ν: frequency, f_ν: flux density at frequency ν (units of f_ν are erg s^{-1} cm^{-2} Hz^{-1}). Since $\int_{\nu_1}^{\nu_2} \nu f_\nu d\nu = \int_{\ln \nu_1}^{\ln \nu_2} f_\nu d \ln \nu$ plotting νf_ν in a log-log-plot gives a measure of the energy emitted per frequency decade.