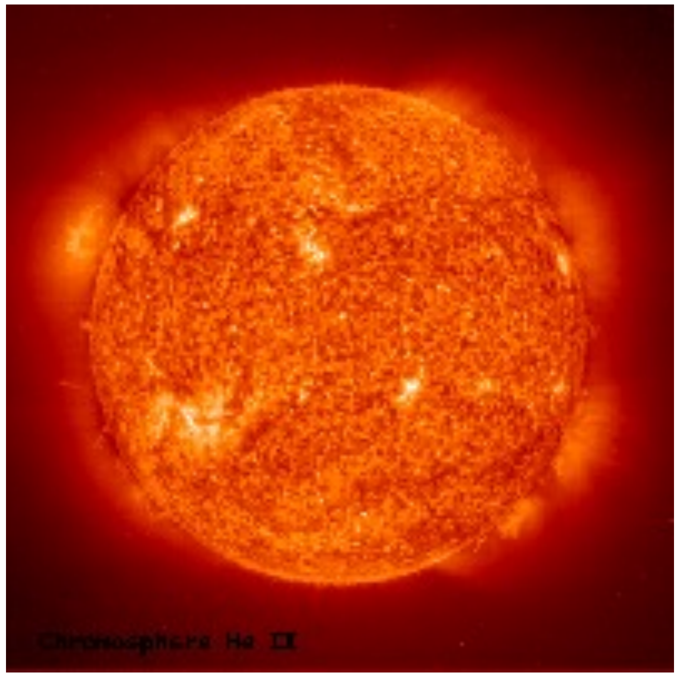
Astronomy 421



Lecture 13: Stellar Atmospheres II

Skip Sec 9.4 and radiation pressure gradient part of 9.3

Announcements:

Homework #4 is due Oct 6

Outline is due October 11

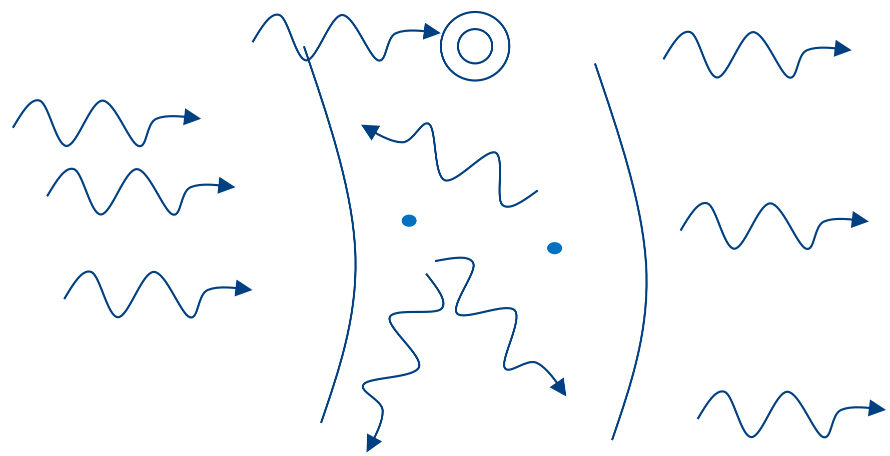
    See example on the class web page

Society of Physics Students – Sign up by Oct 7

- ***Physics Today*** - A monthly award-winning publication*
- ***The SPS Observer*** - A quarterly magazine for undergraduate physics and astronomy students
- SPS News **eNewsletter -** A bi-weekly briefing of everything you need know
- **Jobs:** Access to the SPS Jobs site
- **Careers**: Learn about physicist profiles, Resources and the Careers Toolbox
- **Scholarships:** SPS scholarships include the SPS Leadership, SPS Future Teacher, Community College, and more!
- **Leadership:** Run for the SPS national council
- **SPS Internships** - 10-week-paid internship program for SPS members
- **Travel funds**: SPS Travel awards if you are presenting
- **Science writing**: SPS Reporter awards if you report on a conference
- **Support your mentor**: SPS Outstanding Chapter Advisor award
- **Research awards:** SPS Award for Outstanding Undergraduate Research
- **Host** a regional meeting: SPS Zone Meeting Awards
- Regional (Zone) Meetings
- Attend professional society meetings
- Free membership with two AIP Member Societies for undergraduates only, for up to three years.

https://docs.google.com/forms/d/e/1FAIpQLSf4Gmez_XAru7j6QmtB51LhCkjXbLhkfBJjW_RL0tMo9m9Z0A/viewform?usp=sf_link

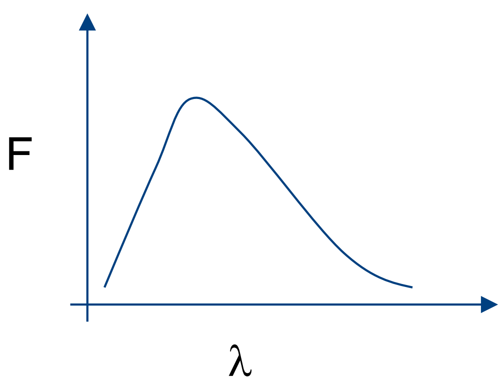
Schematic stellar atmosphere



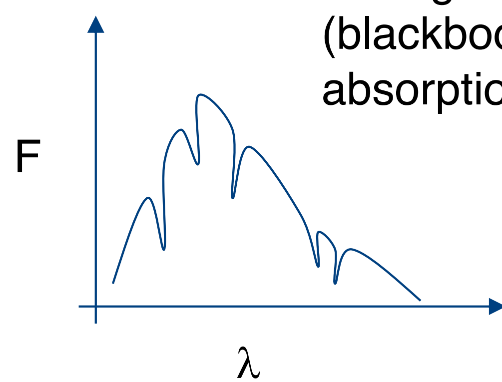
Radiation
from interior
(blackbody)

Atmosphere:
atoms, ions,
electrons

Surface

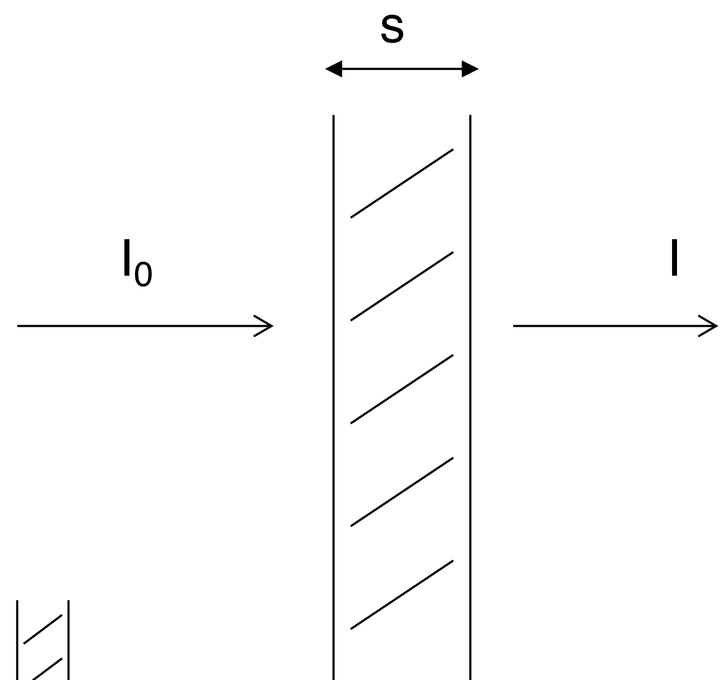


Emergent spectrum
(blackbody +
absorption features).

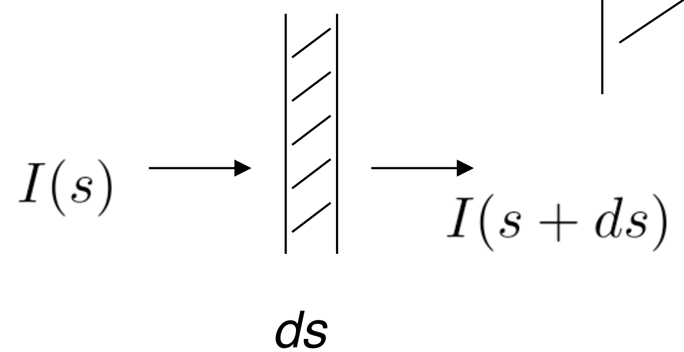


Opacity and Optical Depth

How much energy gets absorbed (or scattered) after passing through the slab?



Divide slab into many thin slabs



Change in intensity across slab: $dI = I(s + ds) - I(s)$

For absorption expect:

1) $dI \propto I(s)$ (why?)

2) $dI \propto ds$ (why?)

3) $dI \propto$ (absorbing ability of material at wavelength in question)

From *1)* set $dI_\lambda = (-d\tau_\lambda) I_\lambda(s)$

proportionality constant TBD

2) $d\tau_\lambda \propto ds$

3) $d\tau_\lambda \propto \kappa_\lambda \rho$

ρ = density of material in slab

κ_λ = *absorption coefficient =* cross section for absorbing + scattering photons per unit mass of material (units $m^2\ kg^{-1}$ or $cm^2\ g^{-1}$).

$$d\tau_\lambda = \kappa_\lambda \rho ds$$

Then $$dI_\lambda = -\kappa_\lambda \rho I_\lambda ds$$

or $$\frac{dI_\lambda}{I_\lambda} = -\kappa_\lambda \rho ds$$

So $$\int_{I_{o,\lambda}}^{I_\lambda} \frac{dI_\lambda}{I_\lambda} = -\kappa_\lambda \rho \int_0^s ds$$

Thus $$I_\lambda = I_{0,\lambda} e^{-\kappa_\lambda \rho s} = I_{0,\lambda} e^{-\tau_\lambda}$$

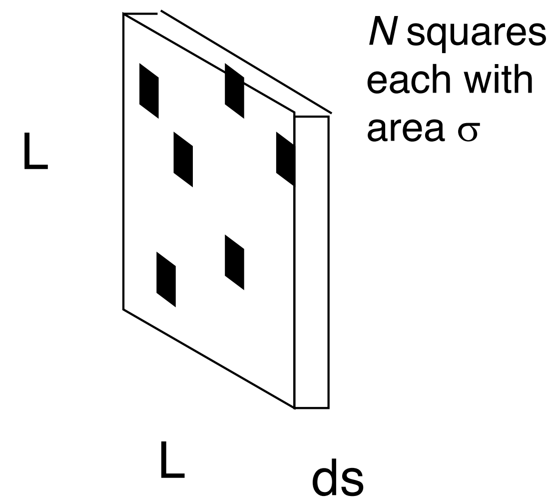
τ_λ is the *optical depth,* and is dimensionless.

A simple way to illustrate: imagine an opaque material consisting of little black squares embedded in clear plastic.

The absorption coefficient depends on projected area of light-absorbing squares and on how many there are per unit mass.

Take a thin slice, so none of the opaque squares overlap.

How much light is lost?



dI/I_0=(total projected area of squares)/(total projected area of slab)

$$\frac{dI}{I_0} = \frac{N\sigma}{L^2}$$

Recall κ = cross section per mass so:

$$\kappa = \frac{N\sigma}{\text{mass of slab}} = \frac{N\sigma}{\rho V} = \frac{N\sigma}{\rho L^2 ds}$$

$$\Rightarrow \frac{N\sigma}{L^2} = \kappa\rho ds$$

$$|\frac{dI}{I_0}| = \kappa\rho ds \text{ and } dI = -I_0\kappa\rho ds$$

$$I_\lambda = I_{0,\lambda} e^{-\kappa_\lambda \rho s} = I_{0,\lambda} e^{-\tau_\lambda}$$

More on optical depths:

Consider $\tau_\lambda = 1$

Then

κ_λ is cross-section per mass, but σ_λ is cross-section per particle. Thus

$$\frac{1}{\kappa_\lambda \rho} = \frac{1}{n\sigma_\lambda} = l$$ mean free path!

Intensity falls by 1/e over one mean free path at λ

$$\tau_\lambda \gg 1 \ \text{optically thick}$$

$$\tau_\lambda \lesssim 1 \ \text{optically thin}$$

Example: Typically, in the Earth's atmosphere κ = 0.0001 cm^2/g, ρ=0.001 g/cm^3. Look through 1 km long slab. What is the optical depth?

$$\tau_\lambda = \kappa_\lambda \varrho s = 0.0001 \times 0.001 \times 10^5 = 0.01$$

(cm^2/g) (g/cm^3) (cm)

What fraction of a light beam with intensity *I* will be blocked and escapes, respectively?

$$I_\lambda = I_{0,\lambda} e^{-\tau} \rightarrow dI_\lambda = I_{0,\lambda} - I_\lambda = I_{0,\lambda}(1 - e^{-\tau_\lambda}) = 0.00995 I_0$$

(what is e^{-x} for small x)?

1% absorbed, 99% transmitted.

Double the length of the slab, what happens to the fraction?

2% absorbed, 98% transmitted.

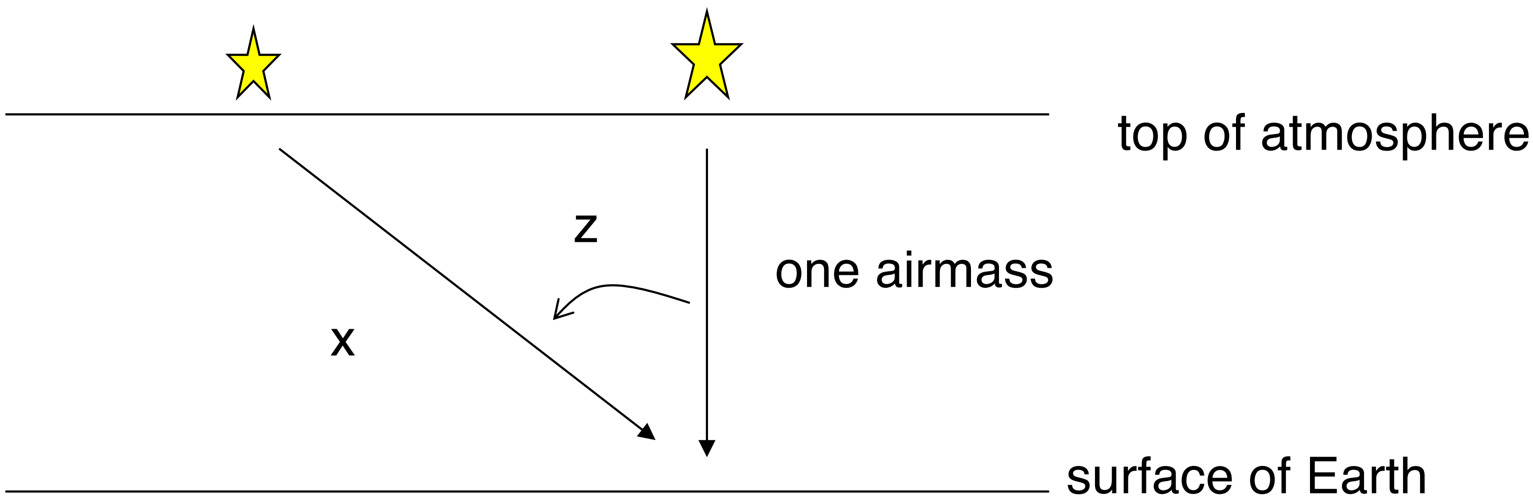
Worksheet: Consider a fairly good day in Pasadena where the density of the atmosphere is about 0.001 g/cm^3 and the opacity is 0.01 cm^2/g. Calculate the optical depth for a path length of 1 km. If the mountains are 5 km away from downtown Pasadena, can you see them? What is the mean free path of a photon through this atmosphere?

$$\tau_\lambda = \kappa_\lambda \varrho s$$

$$I_\lambda = I_{0,\lambda} e^{-\kappa_\lambda \rho s} = I_{0,\lambda} e^{-\tau_\lambda}$$

Example: extinction in the atmosphere of the Earth

Light from star to an observer at the surface of the Earth. Photons may be absorbed or scattered by the atmosphere = *dimming.* The amount of dimming must depend on the amount of atmosphere. The term *airmass* is used to describe this.



one airmass: amount of air directly ahead.

$$\text{airmass}\, x = \frac{\text{one airmass}}{\cos z} = (\text{one airmass}) \sec z$$

Usually, fraction of light loss small and $I(X) = I_0 e^{-cX}$

or, in magnitudes $m(X) = m_0 + kX$

where k= *first order extinction coefficient,* depends on the properties of local atmosphere and wavelength. Typical values for k:

U 0.6

B 0.4

V 0.2

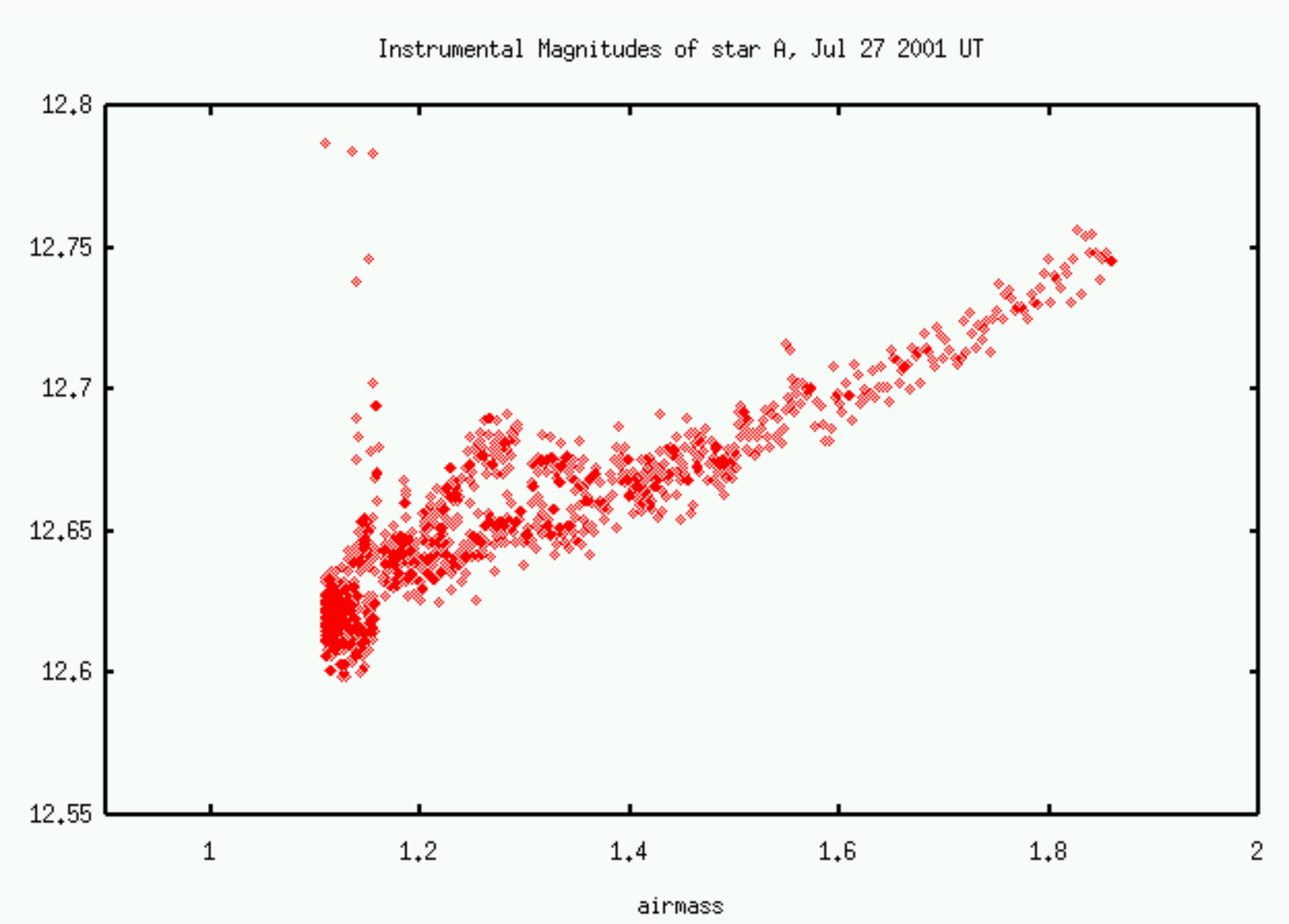
R 0.1

I 0.08

Note: blue light more extinguished than red. Observed especially when sun is setting and rising.

Good observing locations have a small extinction coefficient, and good nights also have small extinction coefficient.

Air changes from night to night, so to correct for extinction we must determine the first order coefficient.



Emergent flux reminder

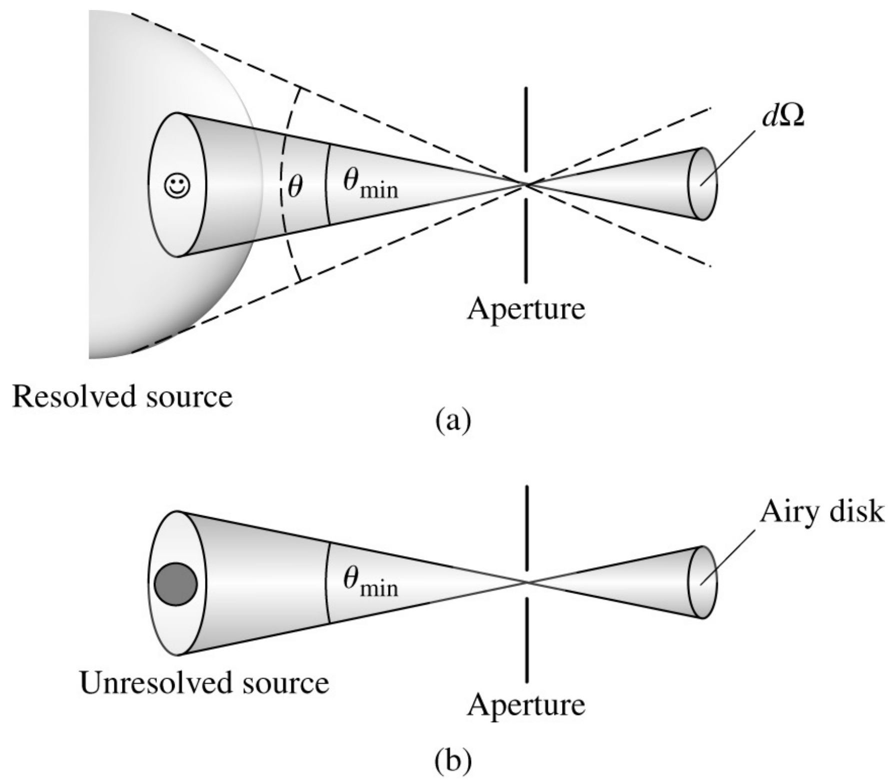
This is the intensity of radiation passing through *dA*, integrated over all angles:

$$F_\lambda d\lambda = \int_\Omega I_\lambda d\lambda \cos\theta d\Omega$$

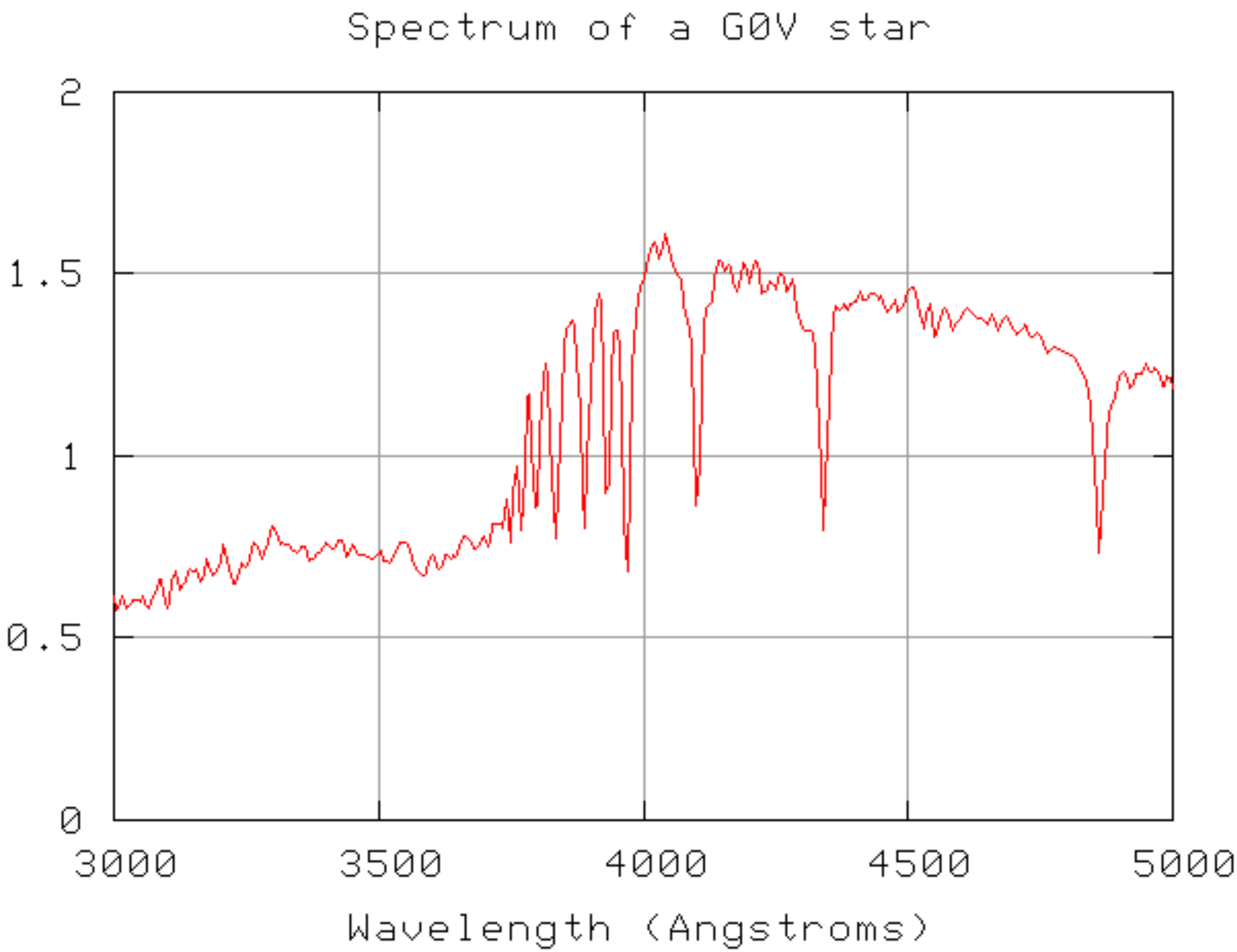
$$\int_\lambda F_\lambda d\lambda \; = \sigma T^4 \text{ for blackbody}$$

What do we measure with a telescope, *F* or *I*?

Depends on whether the source is resolved or not:



In upper plot we measure the specific intensity, while in the lower figure we measure the flux.



Sources of Opacity - How many can you find?

Sources of stellar opacity and emissivity (we won't write eqns for all of these – too complex!):

1) Bound-bound absorption

- When e^- makes upward transition in atom or ion. Subsequent downward transition either:
  - back to initial orbit (effectively a scattering process)
  - back to different orbit (true absorption process for original λ)
  - $\geq$ 2 transitions back to lower levels (true absorption, degradation of average photon energy)
- Call this $\kappa_{\lambda,bb}$. Recall mks units are $m^2\ kg^{-1}$. Is zero except at wavelengths capable of producing upward atomic transitions => absorption lines in stellar spectra. Depends on temperature, abundances, QM transition probabilities. No simple function.

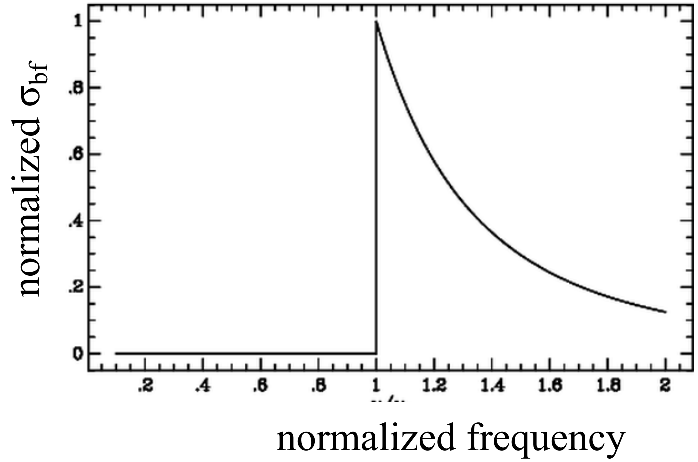
2) Bound-free absorption = photoionization

- $\kappa_{\lambda,bf}$ is a source of continuum opacity. Any photons with $\lambda < hc/\chi_n$ (where χ_n is the ionization potential of n^{th} orbital) can cause ionization. Inverse process: recombination - also degrades photon energies.

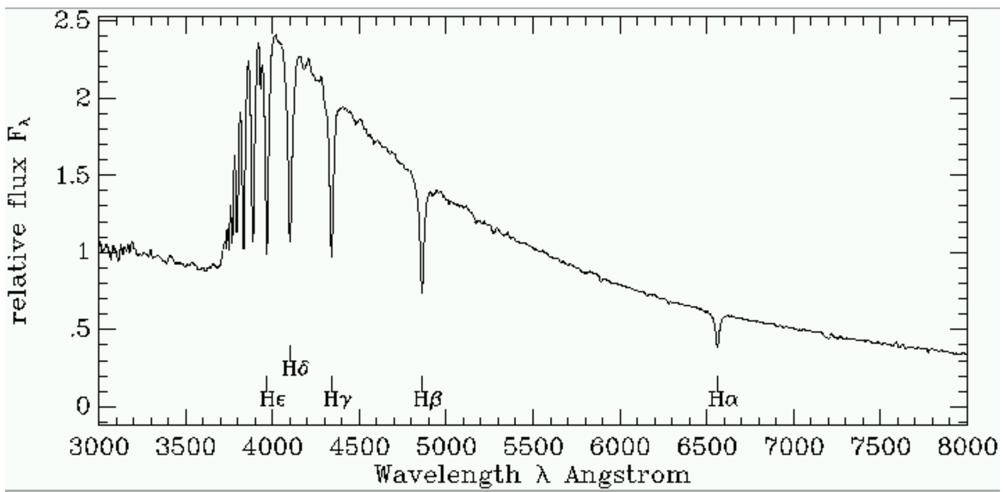
Example: H atom in level *n*

$$\sigma_{bf} = 1.31 \times 10^{-19} \frac{1}{n^5} \left(\frac{\lambda}{500\,\mathrm{nm}} \right)^3 \ \mathrm{m}^2$$

(only for $\lambda \leq \frac{hc}{\chi_n}$; $\sigma_{bf} = 0$ $\lambda > \frac{hc}{\chi_n}$

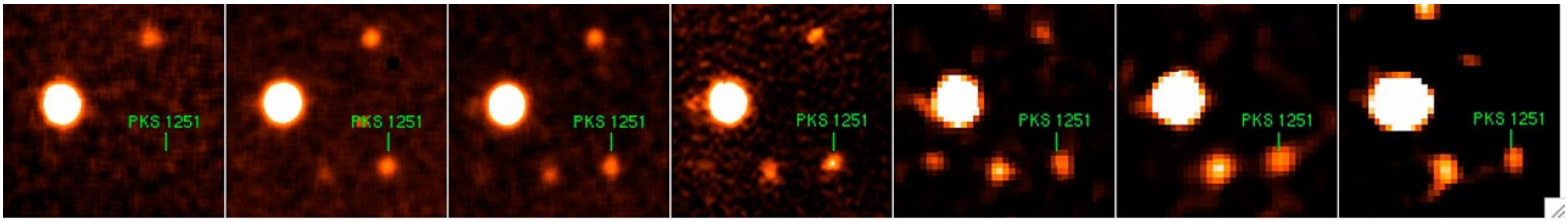


So for level *n*, $\kappa_{\lambda,\mathrm{bf}} = \sigma_{bf}$ times the number of atoms or ions in that level per kg

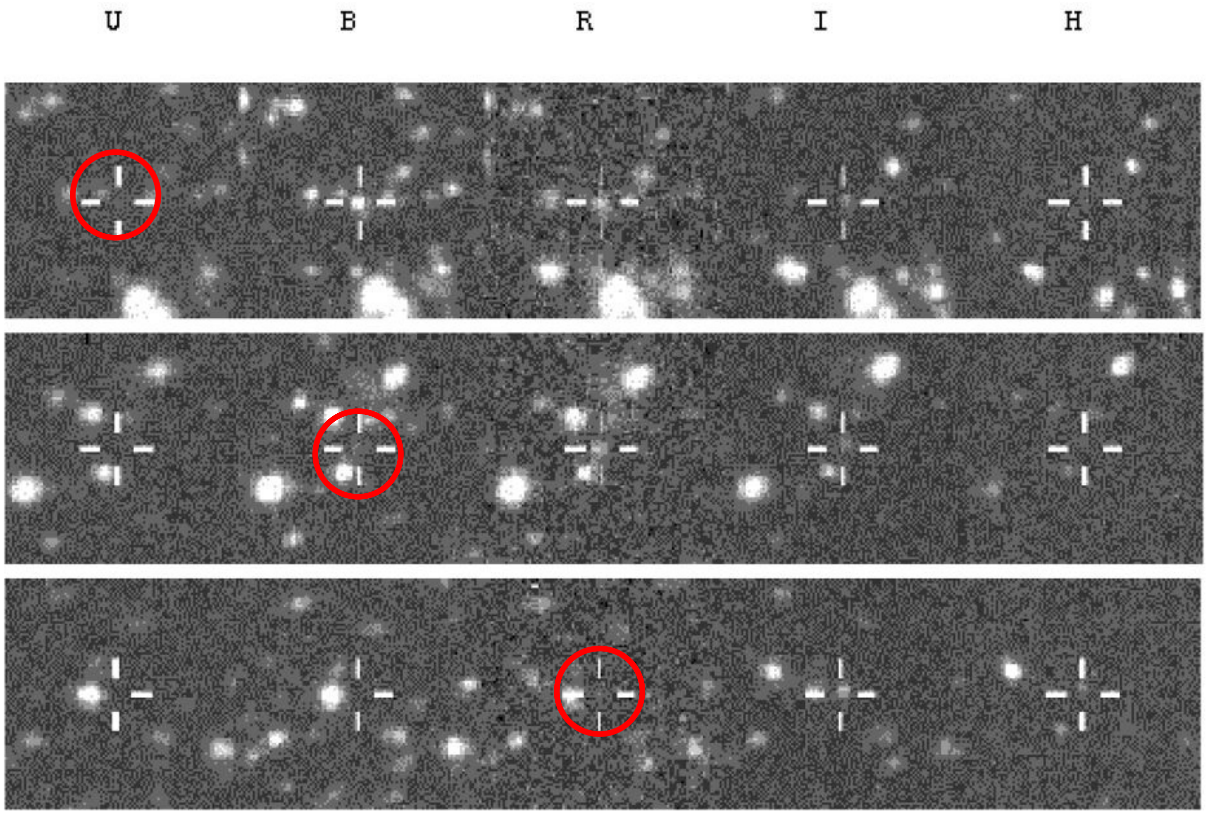


This causes the “Balmer jump”. Photons lost to ionization of H from n=2 level. Requires E ≥ 13.6-10.2 = 3.4 eV, or $\lambda \leq 364.7$ nm. Because $\sigma_{b,f}\ \alpha\ \lambda^3$, spectrum gets closer to blackbody again for shorter λ’s.

Similar jump at E=13.6 eV for Lyman series, but in far UV (except at high redshifts!). Used to get redshifts and thus distances of faint galaxies.



visible → infrared



Which is the most distant object?

3) Free-free absorption

- $\kappa_{\lambda,ff}$: another source of continuum opacity. Free *e*$^-$ near ion absorbs photon and increases velocity.

Why won't isolated e$^-$ absorb photons?

- (converse: free-free emission, or *brehmsstrahlung,* e$^-$ loses energy passing by an ion, emits a photon)

4) Electron-scattering (Thomson scattering)

- κ_{es} : photon scatters off free e$^-$. Source of continuum opacity. Depends on the *Thomson cross section* of the *e*$^-$ (relatively small):

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65 \times 10^{-25}\ \mathrm{cm}^2$$

($r = e/m_e c^2$ often used as the classical 'radius' of an electron)

- But dominates at high-temperatures.

Main source of continuum opacity in stellar atmospheres of type:

F and cooler: Photoionization of H^- ions.

Any photon with

$$\lambda \leq \frac{hc}{\chi} = \frac{hc}{0.754\,\mathrm{eV}} = 1640\,\mathrm{nm} \qquad \text{(IR)}$$

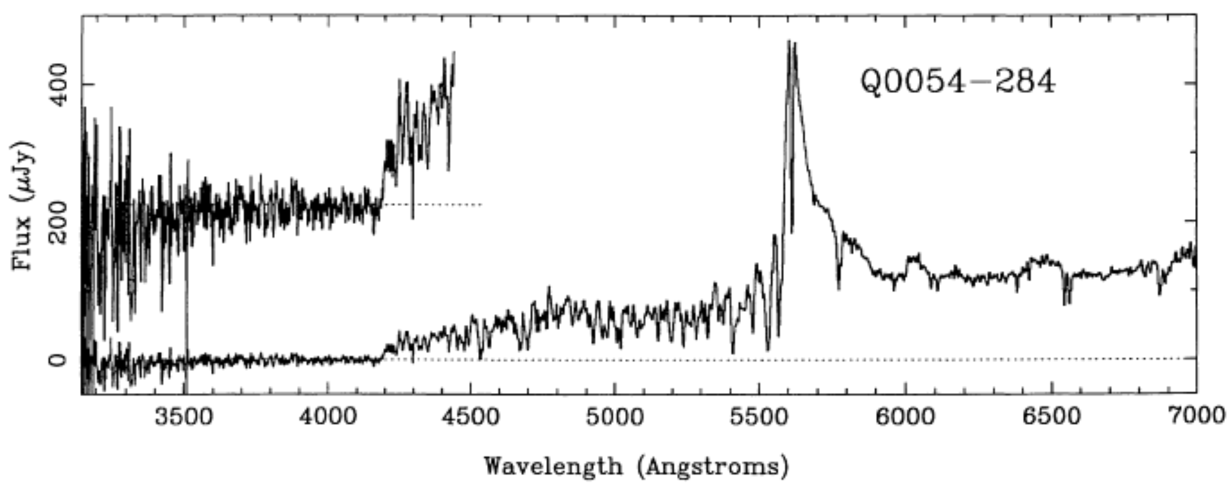
B, A: Bound-free of H and free-free processes

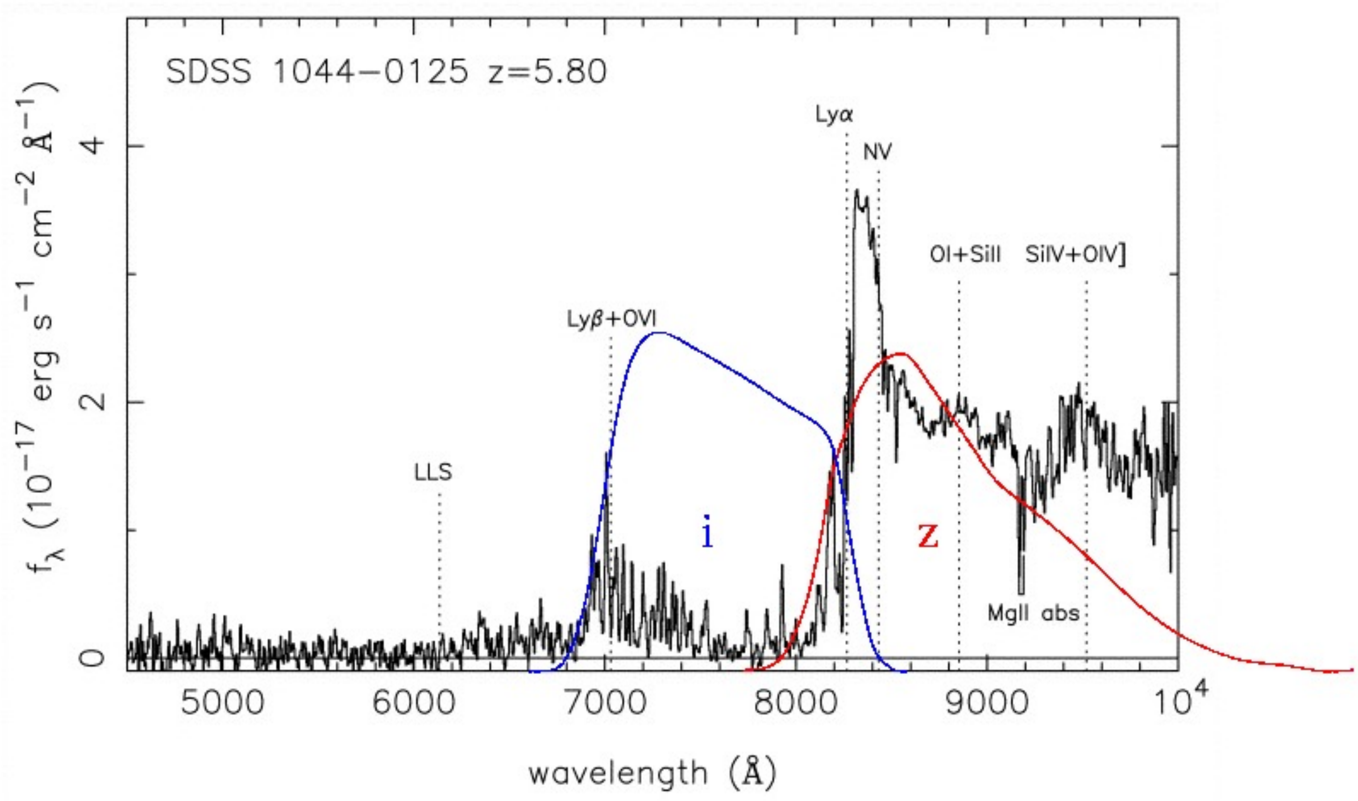
O stars: Electron scattering and bound-free processes of He

Interiors of stars: Electron scattering

There exists a stronger jump, the *Lyman limit,* occurring at the wavelength corresponding to the energy required to ionize an H atom from the ground state (91.2 nm).

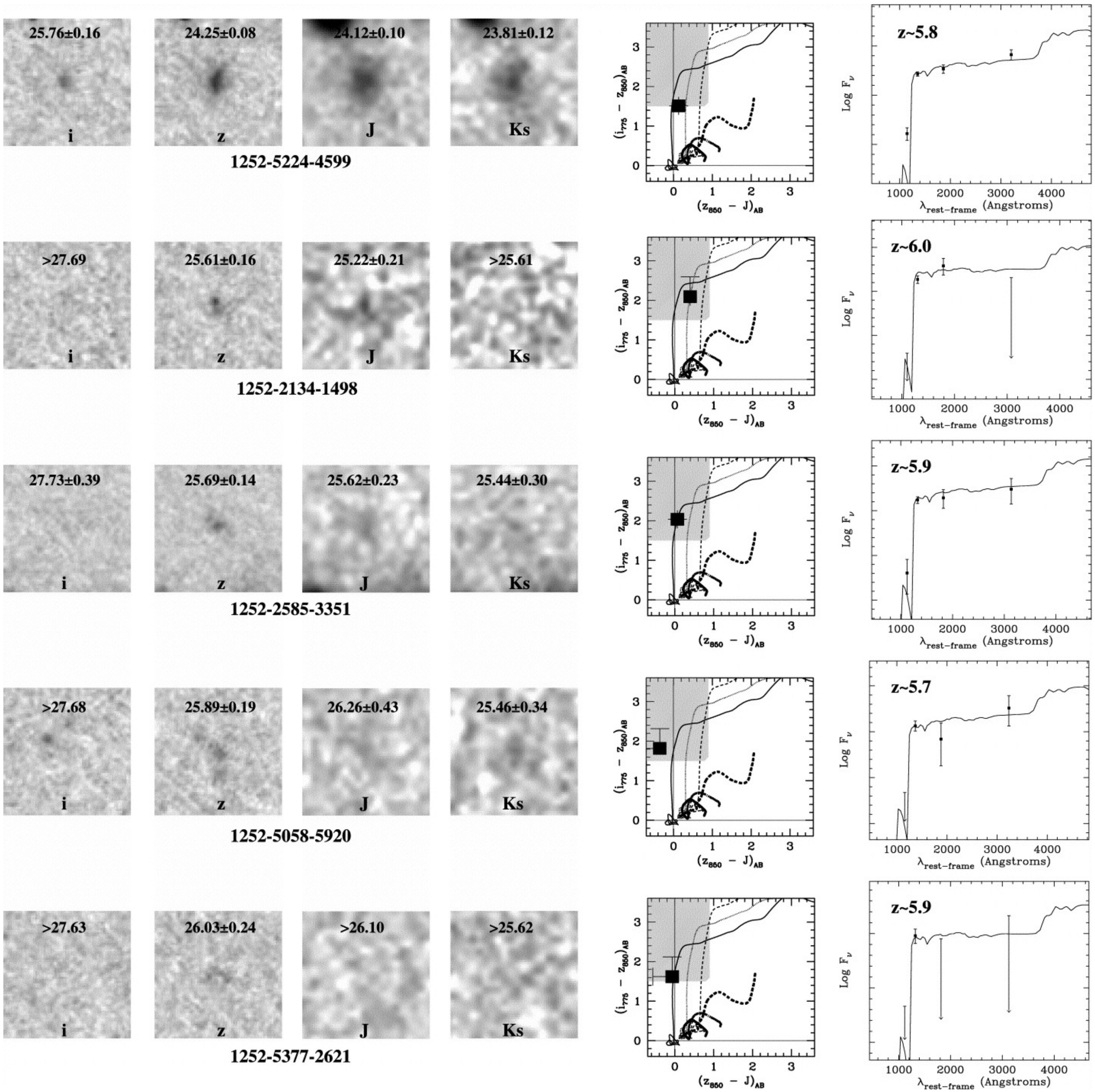
This region is not in the visible, can't be seen from the ground for nearby stars. However, it can be detected in some quasars (why?)





Can be used to search for high-redshift objects, called the 'drop-out' technique.

Look for objects that are faint in the bluest filters.


25.76±0.16
24.25±0.08
24.12±0.10
23.81±0.12
i
z
J
Ks
1252-5224-4599
z~5.8
>27.69
25.61±0.16
25.22±0.21
>25.61
1252-2134-1498
z~6.0
27.73±0.39
25.69±0.14
25.62±0.23
25.44±0.30
1252-2585-3351
z~5.9
>27.68
25.89±0.19
26.26±0.43
25.46±0.34
1252-5058-5920
z~5.7
>27.63
26.03±0.24
>26.10
>25.62
1252-5377-2621
z~5.9
$(i_{775} - z_{850})_{AB}$
$(z_{850} - J)_{AB}$
Log F_ν
$\lambda_{rest-frame}$ (Angstroms)