Matter & Radiation in Astrophysics

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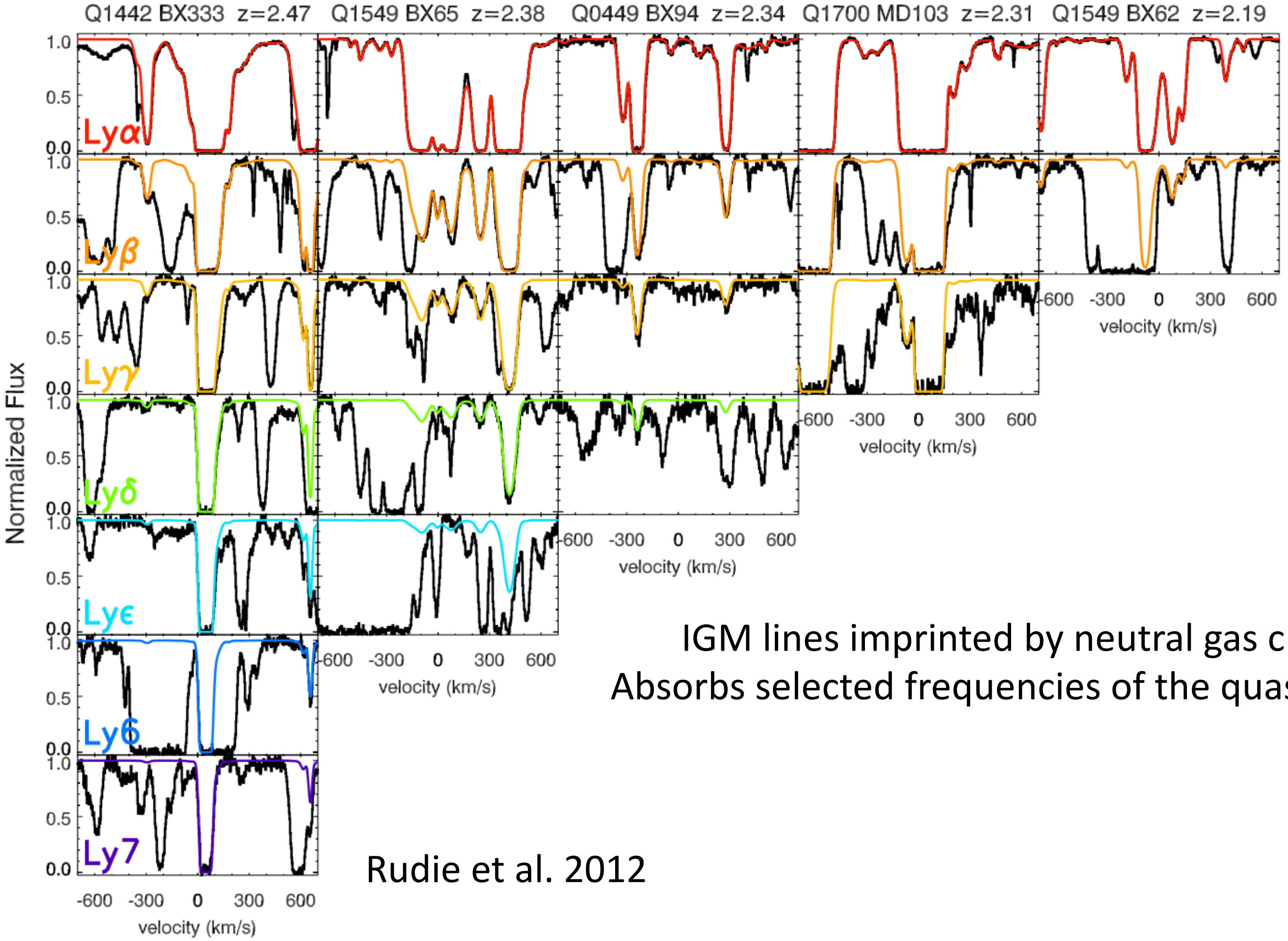
Radiative processes relevant for all fields of astrophysics

Cosmology and the physics of the IGM

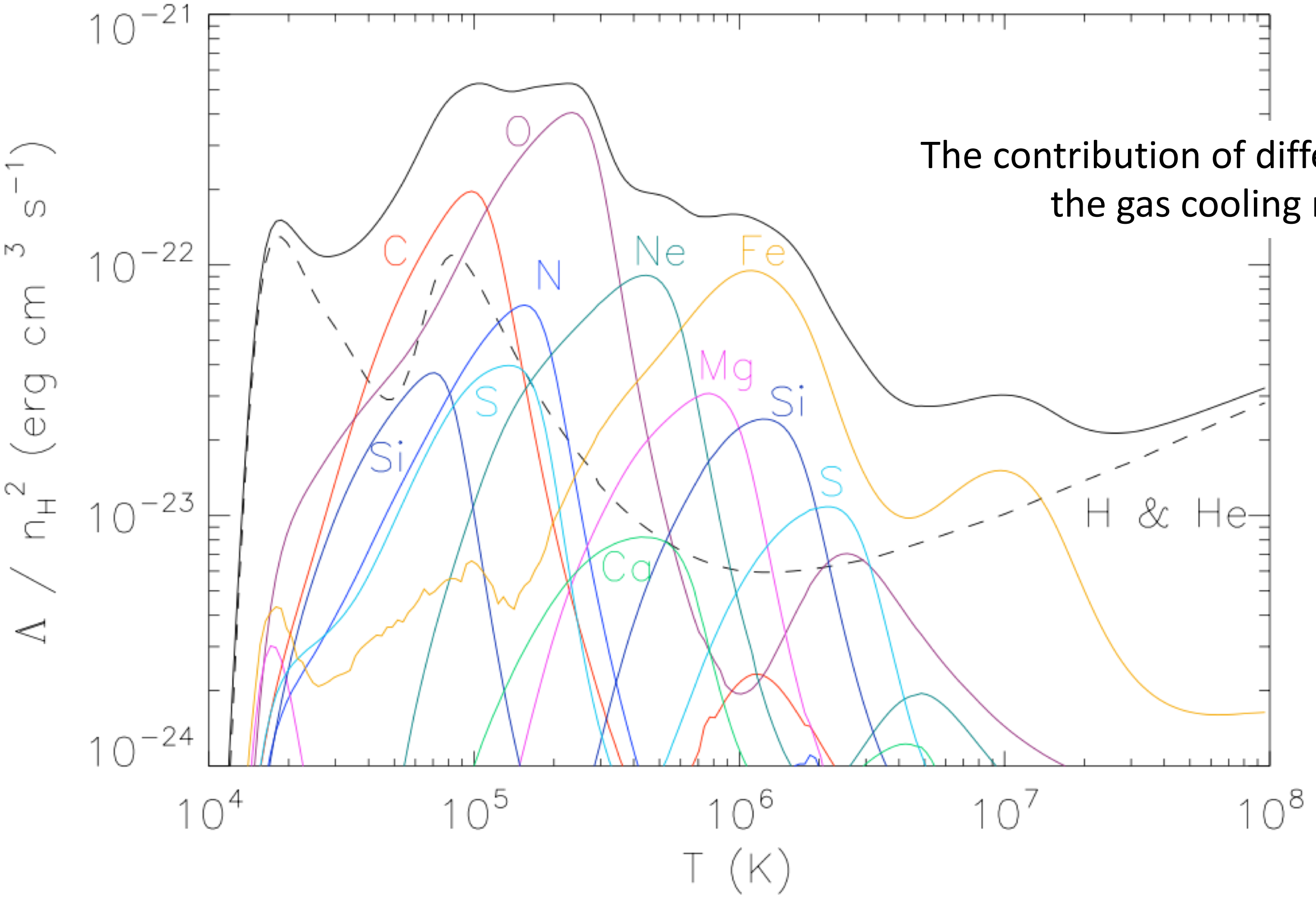


IGM lines imprinted by neutral gas clouds that
Absorbs selected frequencies of the quasar continuum

Rudie et al. 2012

Radiative processes relevant for all fields of astrophysics

Galaxy formation theories

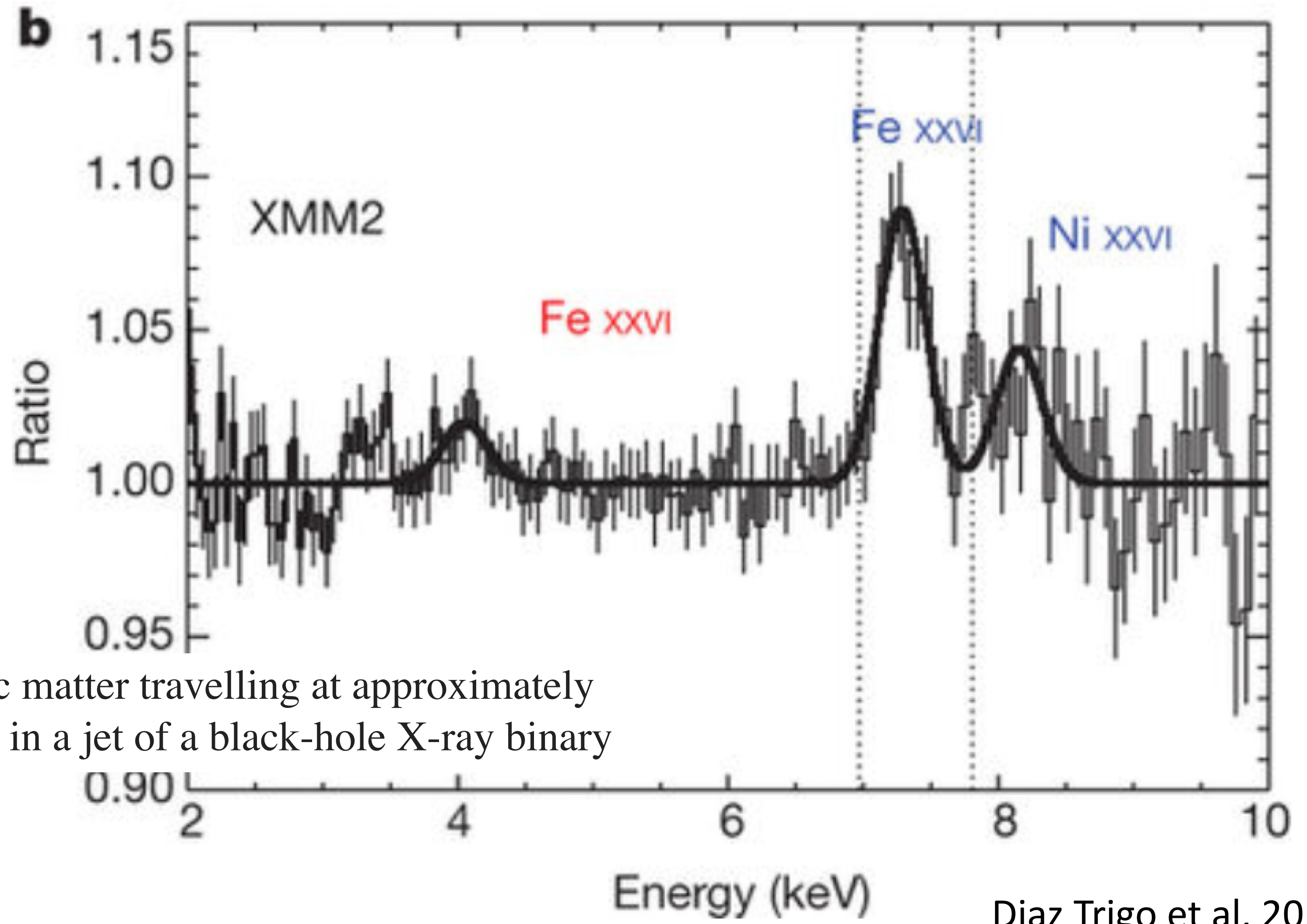


The contribution of different ions to the gas cooling rates

Credit: T Theuns

Radiative processes relevant for all fields of astrophysics

Accreting compact objects

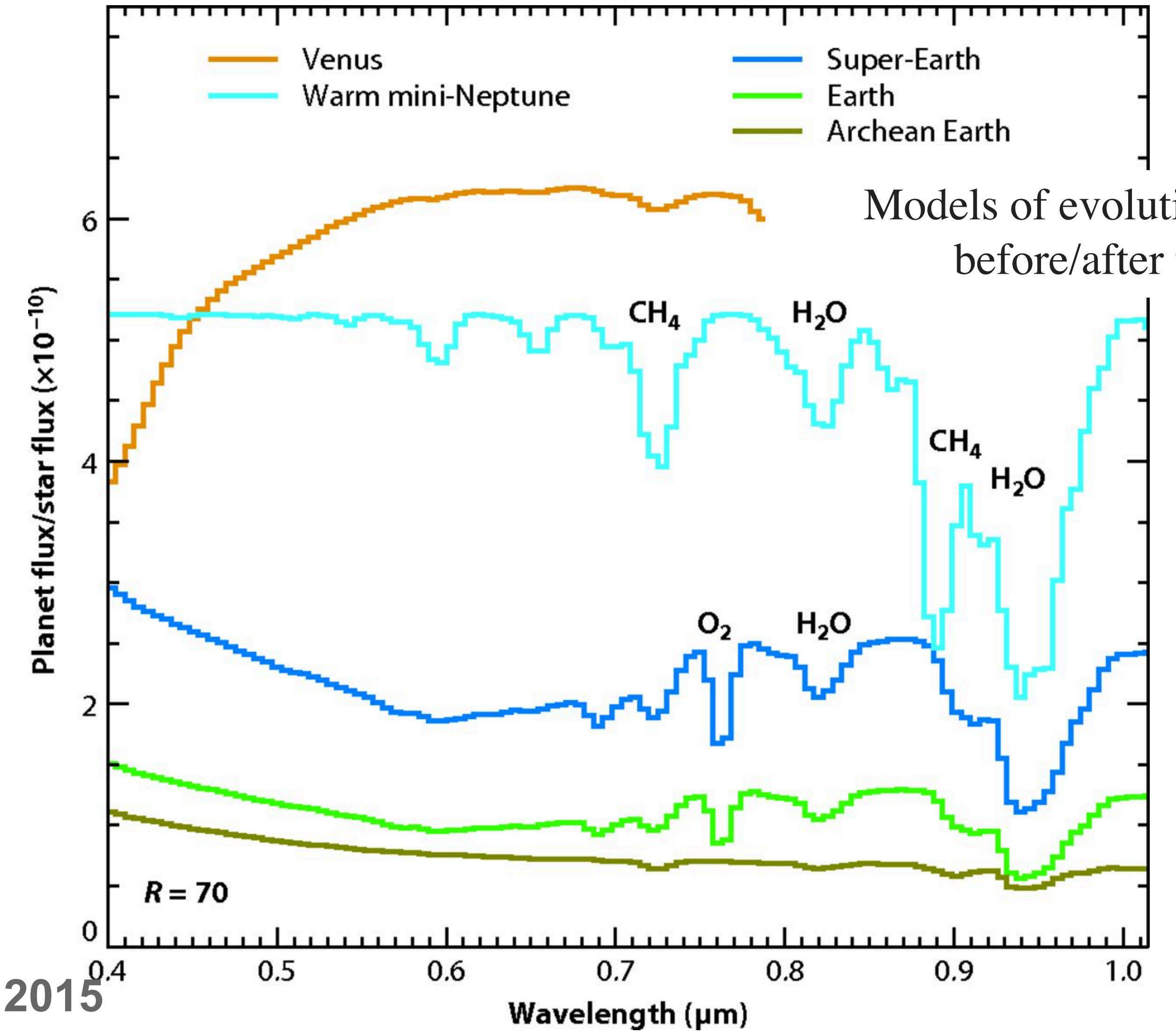


Lines arising from baryonic matter travelling at approximately two-thirds the speed of light in a jet of a black-hole X-ray binary

Diaz Trigo et al. 2013

Radiative processes relevant for all fields of astrophysics

Planet atmospheres

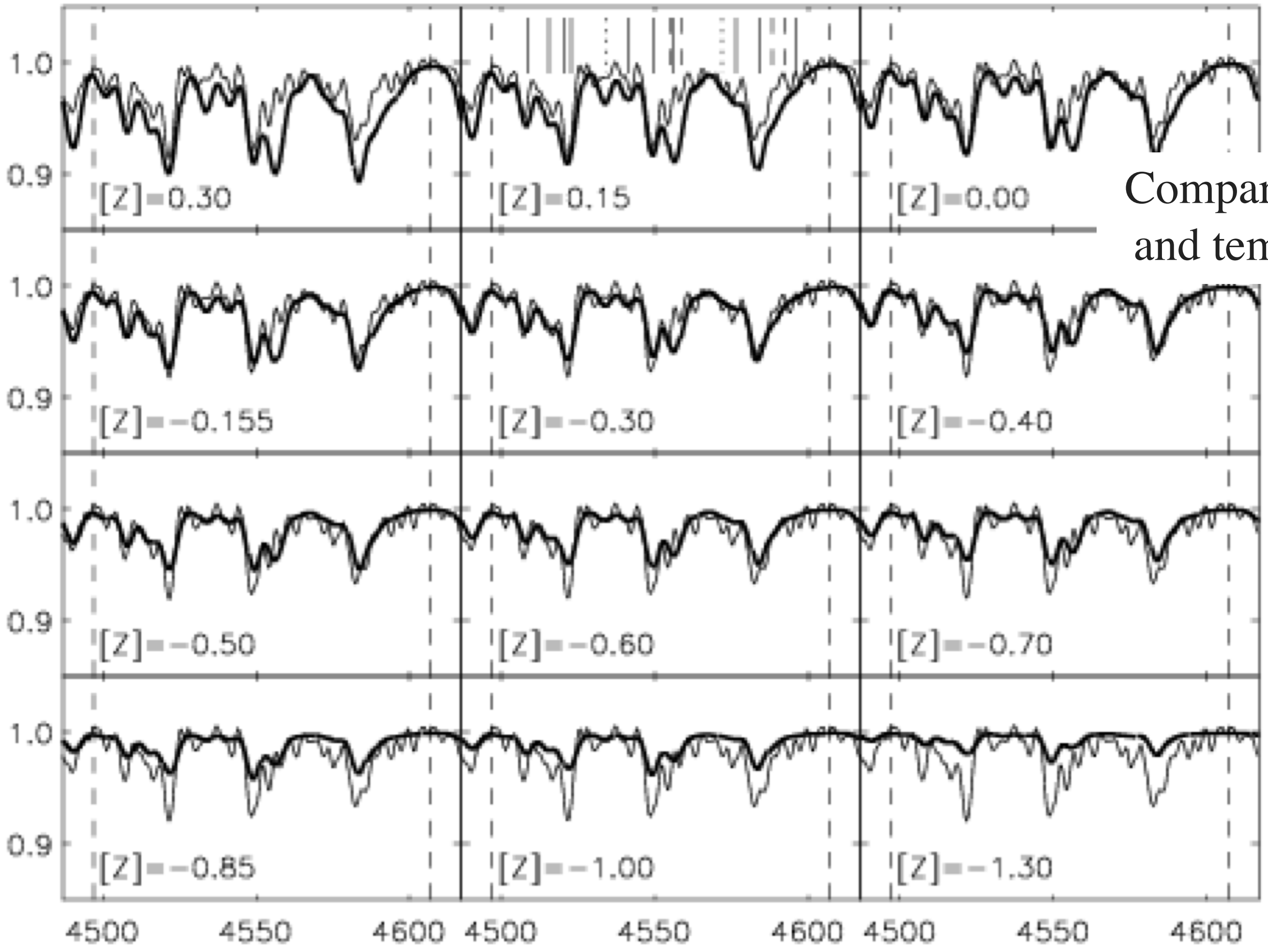


Models of evolution of Earth-like atmospheres before/after the rise of oxygen levels

Seager & Bains 2015

Radiative processes relevant for all fields of astrophysics

The properties of galaxies

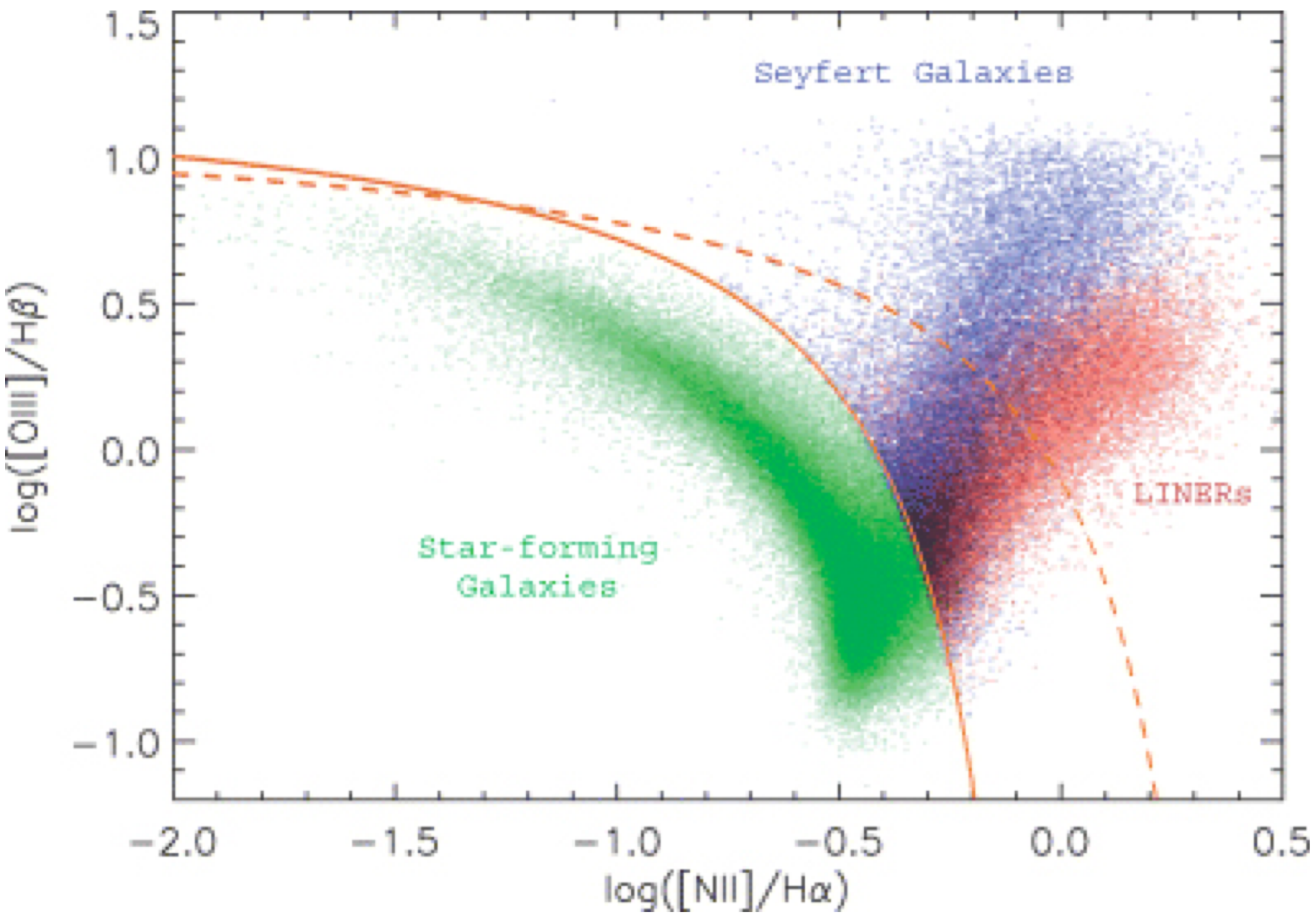


Comparison between absorption lines and templates at different metallicity

http://inspirehep.net/record/782038/files/fig4a.png

Radiative processes relevant for all fields of astrophysics

The properties of galaxies



BPT diagram

“Practical” outline (cloudy)

1. Basic of radiative transfer
2. Reaction in the ISM and dust
    1. Radiative transfer through dust
3. Interaction matter/radiation and line formation
    1. Gas in radiation field
    2. Ionization stages in the ISM/CGM/IGM
4. Photoionization equilibrium
    1. HII regions
5. Heating and cooling and the thermal history of the Universe
    1. Heating and cooling function
    2. Temperature/density sensitive lines

Cloudy (Ferland et al. 1998)

Useful to understand how microphysics maps into macroscopical properties

http://adsabs.harvard.edu/abs/1998PASP..110..761F
http://www.nublado.org/

Instructions to download and install cloudy at:

https://www.nublado.org/wiki/StepByStep

Make sure you run the smoke test to verify the installation

Running a basic model

Inside “test.in” (where the magic happens):

```
table power law // a built-in power-law continuum
phi(H) 18.5 // the log of the flux of H-ionizing photons [cm-2 s-1]

hden 10 // log of hydrogen density cm-3
stop column density 22 // log of hydrogen column density cm-2

iterate to convergence
save overview last ”test.ovr"
save continuum last ”test.con"
```

Shape and intensity of radiation field

Properties of material

Controlling code/output

Pay attention to…

3.2 The geometry—intensity & luminosity cases

The brightness of the radiation field striking the cloud can be specified as an intensity or luminosity. It must be possible for the code to deduce the energy striking a unit area of the cloud. The subsection *Intensity vs luminosity commands* of Part 1 of HAZY describes the distinction between these two cases.

In the intensity case the energy flux (erg cm^{-2} s^{-1}) or photon flux (cm^{-2} s^{-1}) striking a unit area of cloud is set. The inner radius does not need to be specified. The emission per unit area [erg cm^{-2} s^{-1}] is predicted[2].

In the luminosity case the total luminosity of the central source of radiation is specified and the inner radius of the cloud must be set. The luminosities of emission lines [erg s^{-1}] are predicted.

Pay attention to…

3.5 What sets the outer edge to the cloud? Why should the calculation stop?

The code starts at the illuminated face of the cloud and works its way into deeper regions. This integration must stop for some reason. In many cases the outer edge of the simulation is not the outer edge of the cloud but rather the region where the gas has become cold and neutral. In other cases the column density of the cloud may be known from observations. Many different stopping criteria can be specified and the code will stop when the first one is reached.

Cloudy was originally designed to interpret optical/UV emission lines in quasars. These lines are produced in warm ionized gas so the default is to stop the calculation when the gas temperature falls below 4000 K. This will often be near the hydrogen ionization front. This would be a mistake if you want to consider cool atomic or molecular regions.

You should understand what sets the outer edge of the cloud you wish to simulate and then confirm that the code reached that point. The introduction to the chapter *Stopping Criteria* of Part 1 of HAZY goes into this in more detail.

Pay attention to…

4.1 Chemical composition

The composition is set by specifying the abundances of the lightest 30 elements. Abundances are specified by number relative to hydrogen. On this scale a typical carbon abundance is $n(\mathrm{C})/\mathrm{n(H)} \approx 2 \times 10^{-4}$.

4.1.1 Commands normally used

Frequently-used commands follow:

abundances sets the abundances of all elements to the values given on the line. If no numbers are present but a keyword is given then the composition is set to a standard mixture. Examples include the local ISM or a typical planetary nebula. Grains are included in some abundances sets. Consult the ***Chemical Composition*** chapter of Part 1 of HAZY to find out more.

element sets the abundance of a particular element, removes the element from the calculation, or specifies its ionization state.

grains determines the type and abundance of grains. If grains are included then, by default, their abundance will be the same across the cloud and quantum heating will be included when it is important. The **function** keyword will make the grain abundance depend on position and the **no qheat** keyword will turn off quantum heating. By itself this command specifies classical or large grains but does not include PAHs.

Running a basic model

Check that all went as expected

> tail –n 10 test.out

```
----------------Convergence statistics----------------
      3.8 mean iterations/state convergence
     2.59 mean cx acceleration loops/iteration
     1.34 mean iso convergence loops/ion solve
        1 mean steps/chemistry solve
        1 mean step length searches/chemistry step
-------------------------------------------------------

 Cloudy ends: 276 zones, 4 iterations. (single thread) ExecTime(s) 378.74
 [Stop in cdMain at maincl.cpp:517, Cloudy exited OK]
```

Running a basic model

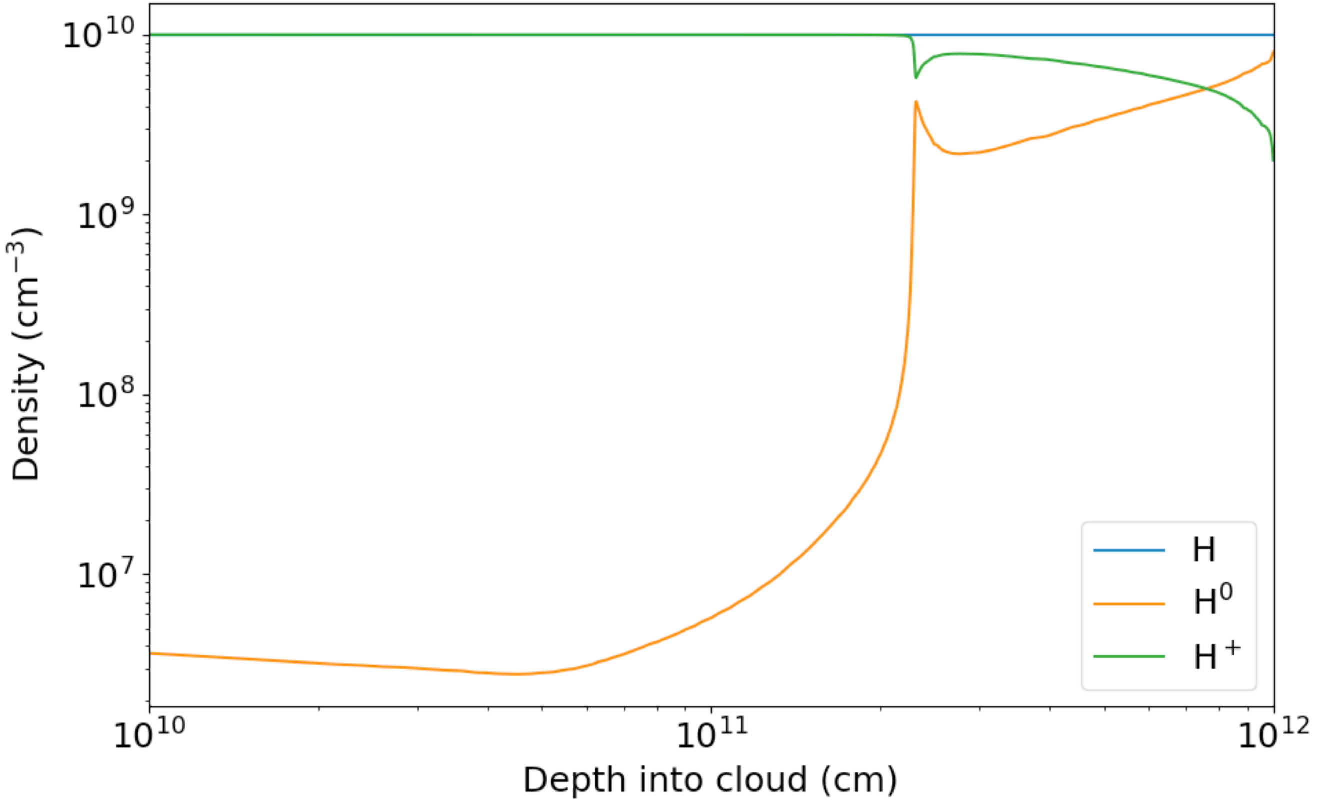
Analyze the outputs

```
"""
Plot the density of the test model
"""


from astropy.table import Table
from matplotlib import pyplot as plt
import matplotlib

font = {'size':18}
matplotlib.rc('font', **font)

#load the data
model=Table.read('models/test.ovr',format='ascii')
plt.loglog(model['depth'],model['hden'],label='H')
plt.loglog(model['depth'],model['HI']*model['hden'],label=r'H$^0$')
plt.loglog(model['depth'],model['HII']*model['hden'],label=r'H$^+$')
plt.xlim([1e10,1e12])
plt.xlabel('Depth into cloud (cm)')
plt.ylabel('Density (cm$^{-3}$)')
plt.legend()
plt.show()
```



More advanced models

All you need to know (and more) in the manuals:

Quick start https://www.dropbox.com/s/y5kk2leei512r74/QuickStart.pdf?dl=0

Full version https://www.dropbox.com/s/pmogr1yny27e5gx/hazy1.pdf?dl=0

Problem 1 (Workshop): Radiative transfer through dust

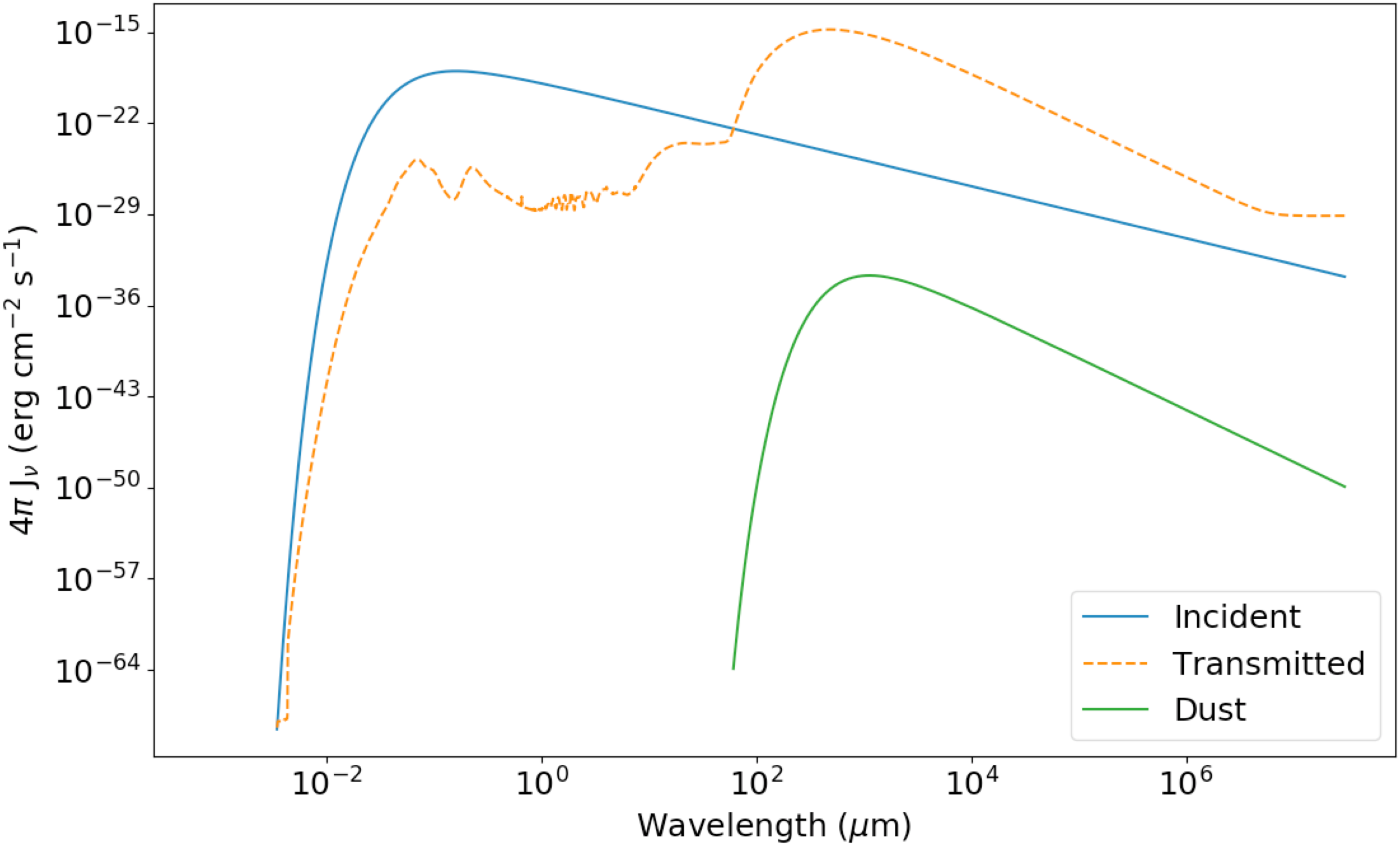
Aim: Study the radiative transfer equation through a dusty medium (e.g. stars behind a dust cloud, AGNs behind a torus, …)

Set up:

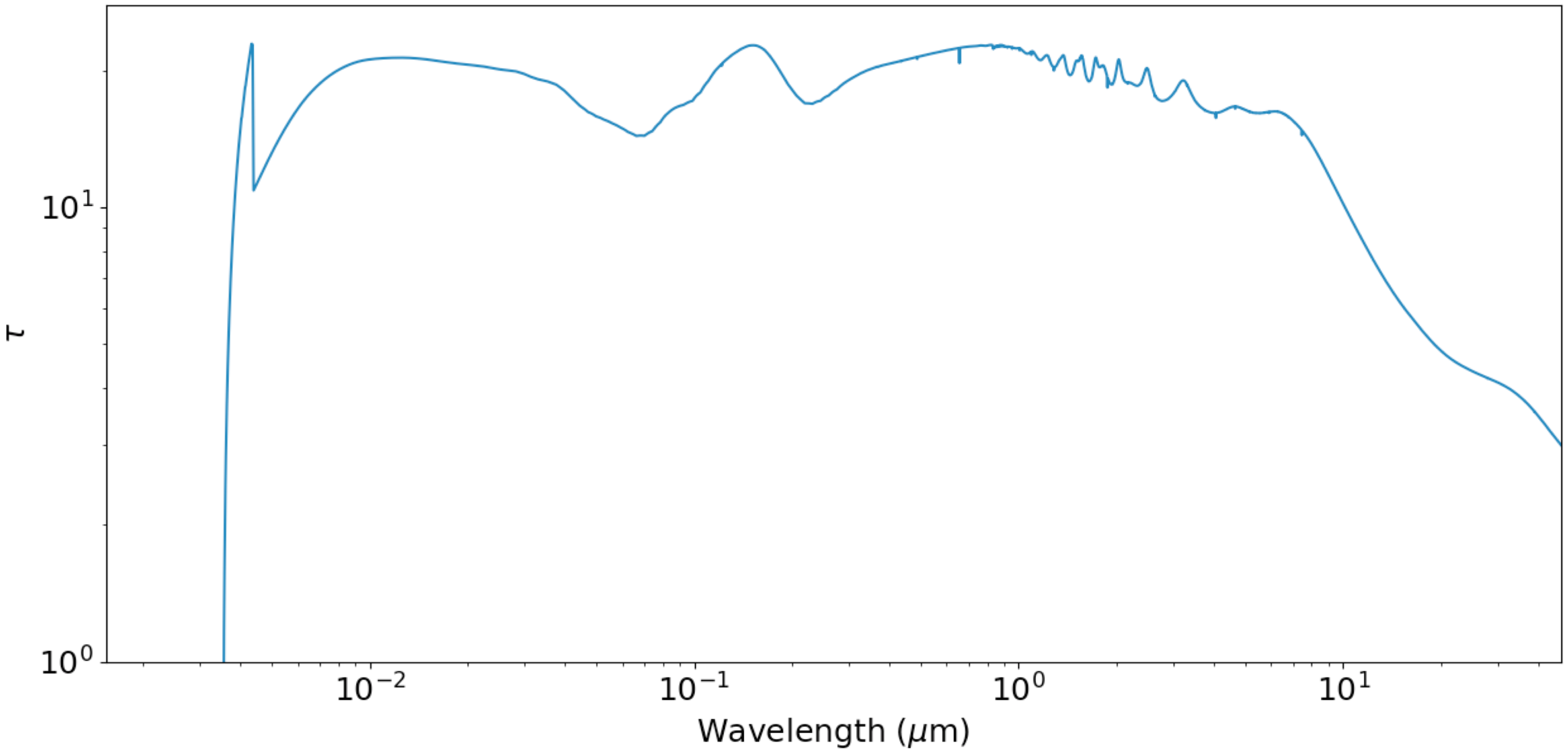
```
blackbody 4.5 //spectral shape (BB of log T)
intensity -2.8, range 0.44 to 1 Ryd //set intensity to Habing 1968 radiation field
radius 10 to 10.5 linear parsecs // inner radius 10 pc, outer 10.5 pc
hden -4 // log of hydrogen density cm-3
abundances PRIMordial //primordial composition
grains "graphite_1m000.opc" 1e10 //grains of 1 mu in size
no scattering opacity // turn off scattering by dust
no grain qheat //turn off quantuum heating
grains no reevaluate //speed up convergence
iterate to convergence
save overview last "dustBB.ovr"  //save some general properties
save incident continuum last "dustBB.incon" units Hz //save incident continuum
save transmitted continuum last "dustBB.outcon" units Hz //save transmitted continuum
save grains last "dustBB.grains" opacity units Hz //save opacity of grains
save grain continuum last "dustBB.gracon" units Hz //save IR emission from grains
save grain abundance last "dustBB.graabn" //save grain abundance
```

Tasks:

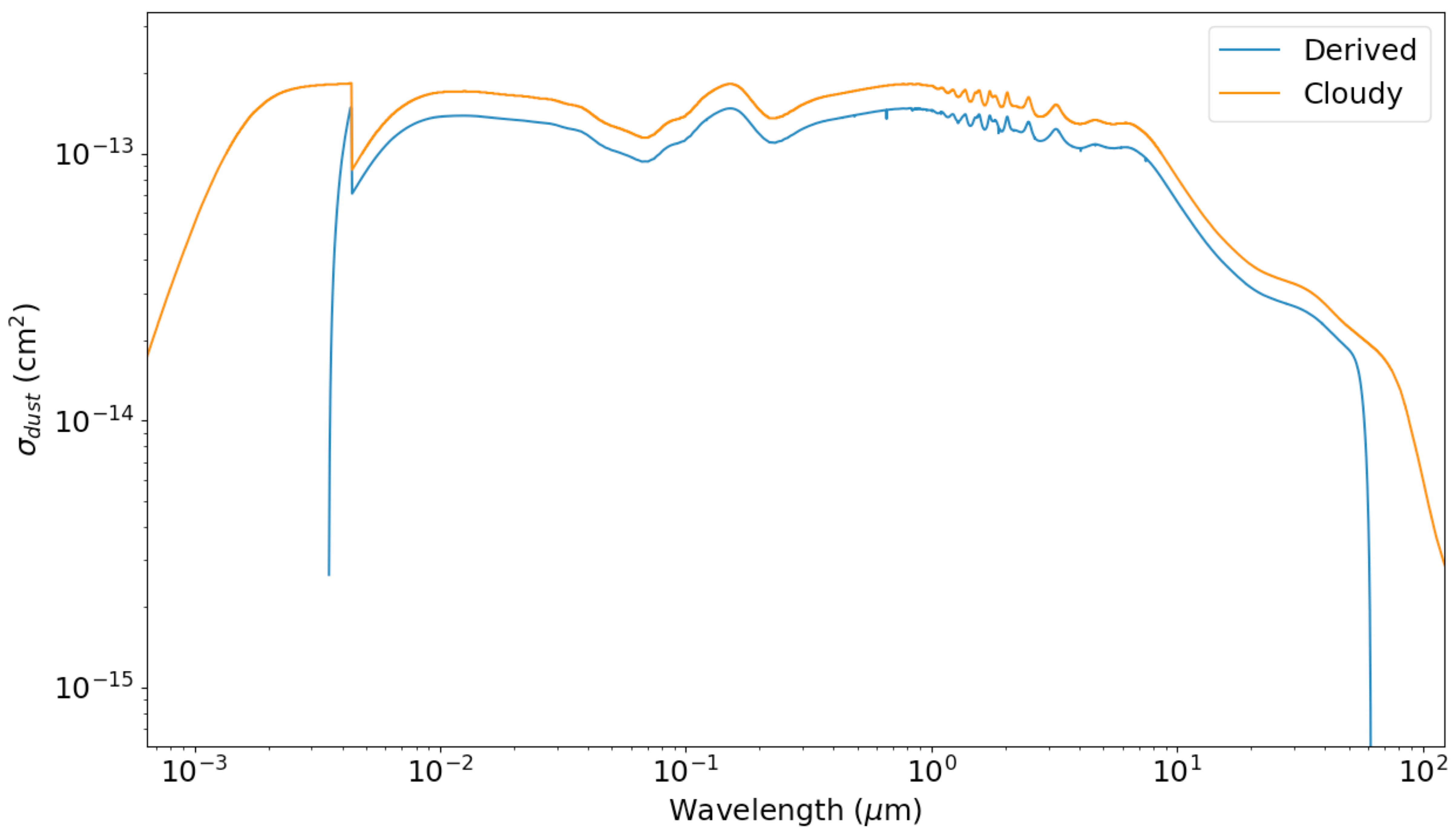
1. Compare the incident and emitted intensity and derive the dust optical depth.
2. Derive the cross section for dust absorption. You will need the dust mass (given at the beginning of the .out file), and the dust density (given in the .graabn file).
3. Compare your result with the Cloudy one (given in the .grains file).
4. Repeat your calculation for smaller dust grains (graphite_0m100.opc).
5. Repeat your calculation including scattering.



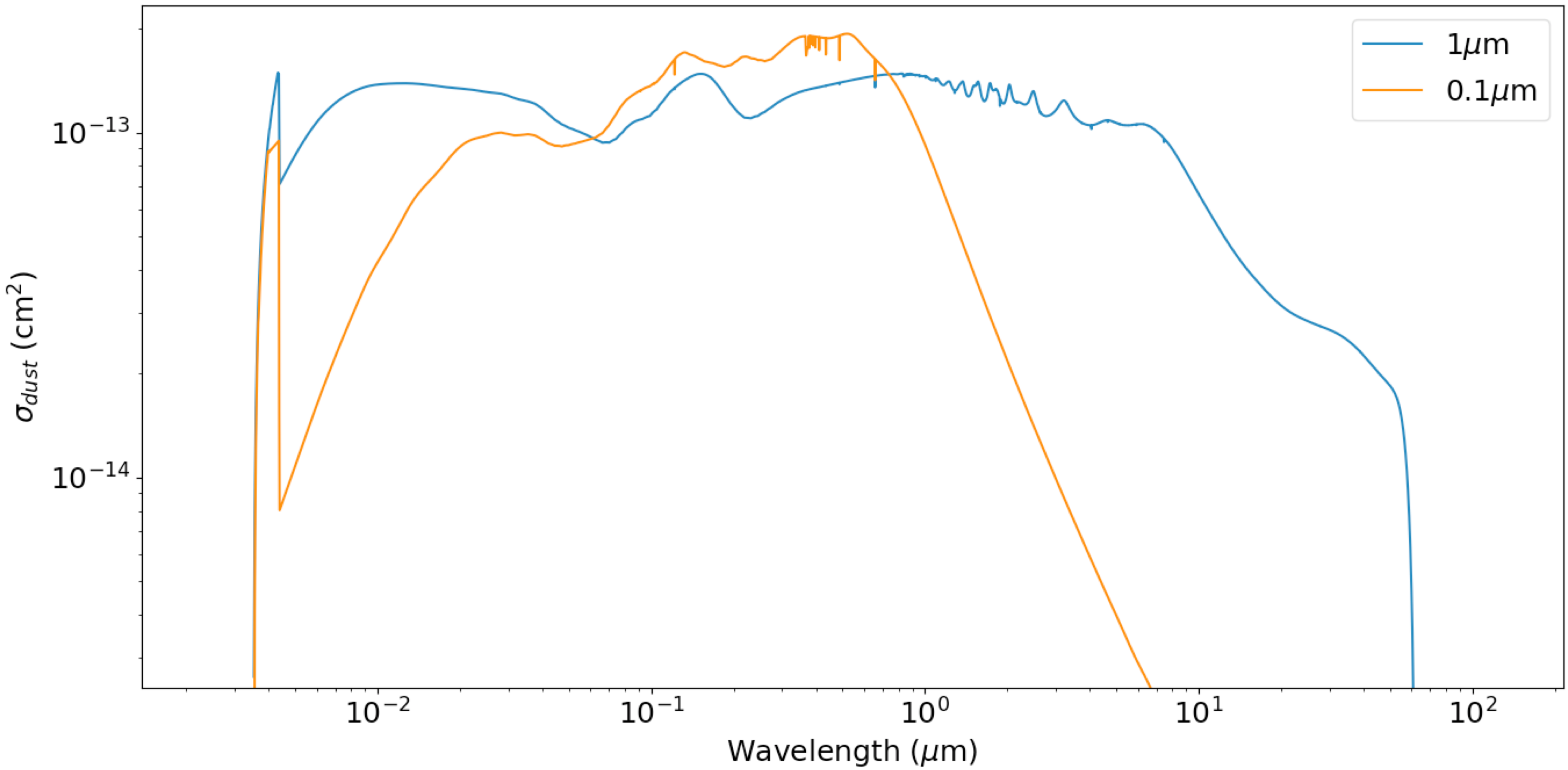
10^{-15}
10^{-22}
10^{-29}
10^{-36}
10^{-43}
10^{-50}
10^{-57}
10^{-64}
4π J$_\nu$ (erg cm^{-2} s^{-1})
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Wavelength (μm)
Incident
Transmitted
Dust



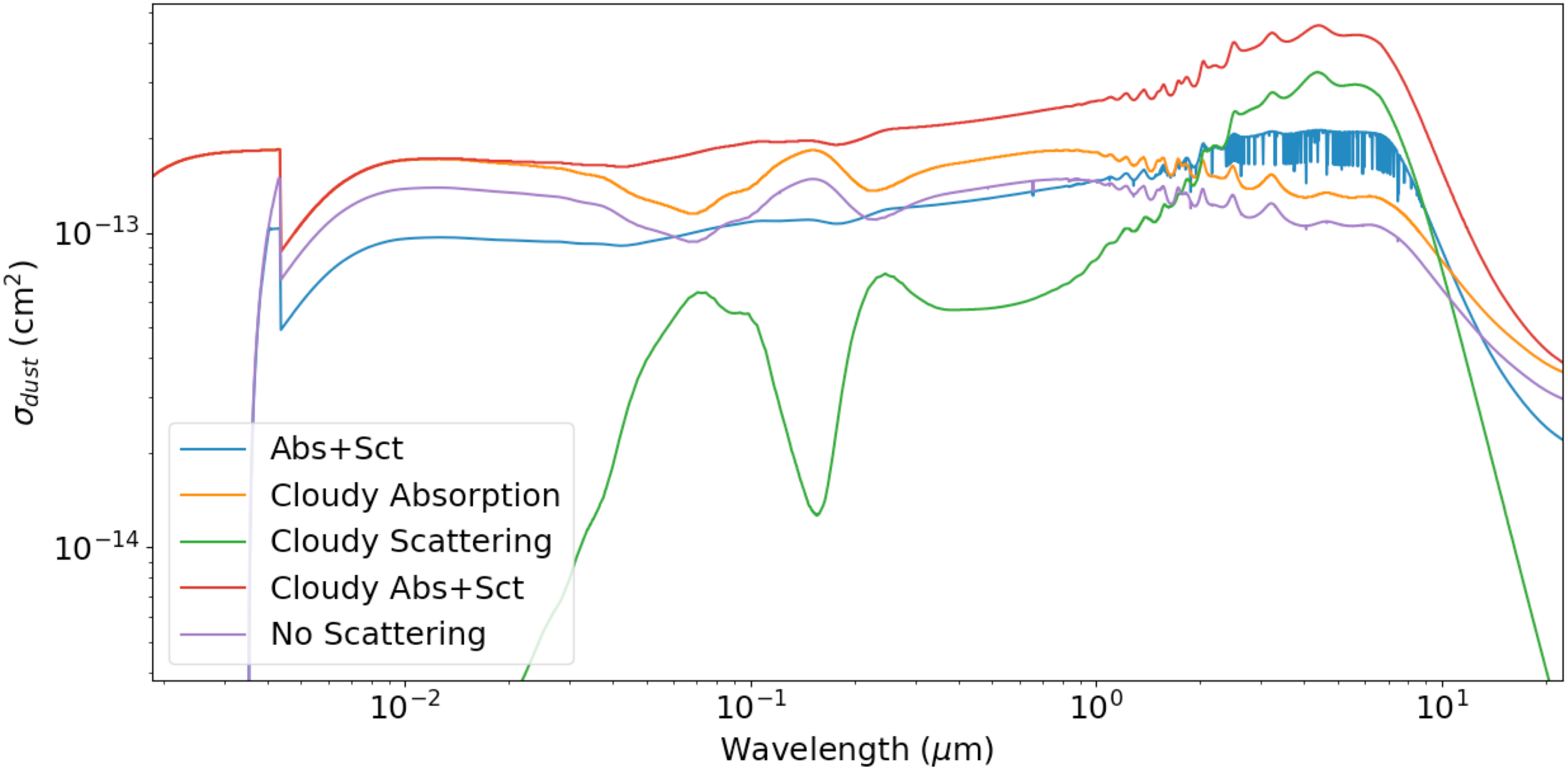
10^1
10^0
τ
10^{-2}
10^{-1}
10^0
10^1
Wavelength (μm)



Derived
Cloudy
10^{-13}
10^{-14}
10^{-15}
σ_{dust} (cm^2)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Wavelength (μm)



1μm
0.1μm
10^{-13}
10^{-14}
σ_{dust} (cm^2)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Wavelength (μm)



σ_{dust} (cm^2)
10^{-13}
10^{-14}
10^{-2}
10^{-1}
10^{0}
10^{1}
Wavelength (μm)
Abs+Sct
Cloudy Absorption
Cloudy Scattering
Cloudy Abs+Sct
No Scattering

Problem 2 (Workshop): Cloud in a radiation field

Aim: Study the bound-bound and bound-free transitions of a cloud inside a radiation field

Set up:

```
Table HM05 redshift 3.0 //the UVB at z~3
radius 10 to 10.5 linear parsecs // inner radius 10 pc, outer 10.5 pc
hden 0 // log of hydrogen density cm-3
abundances all -20 //create a mixture of H,He
element abundance helium -1
iterate to convergence
save overview last "edge.ovr"  //save some general properties
save incident continuum last "edge.incon" units eV //save incident continuum
save transmitted continuum last "edge.outcon" units eV //save transmitted continuum
stop temperature 1000 K
```

Tasks:

1. Derive the optical depth.
2. Explain the origin of the features visible between 10-60 eV.
3. Compare the cloudy calculation with bound-bound and bound-free transitions of H and He+ using the Rydberg formula. What happens to H Lya?
4. Repeat your calculations for different densities. What happens and why?
5. Repeat your calculation for gas cloud at 2.5e4 K (use "constant temperature" command). What happens and why?

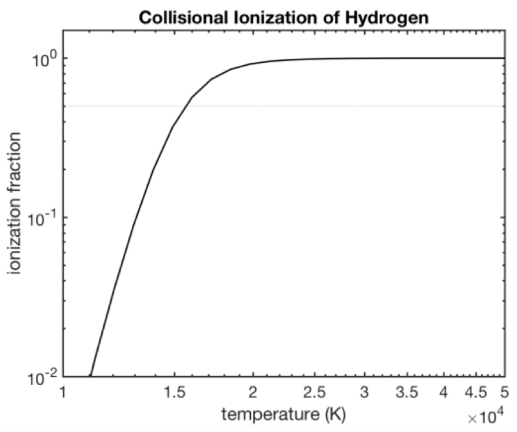
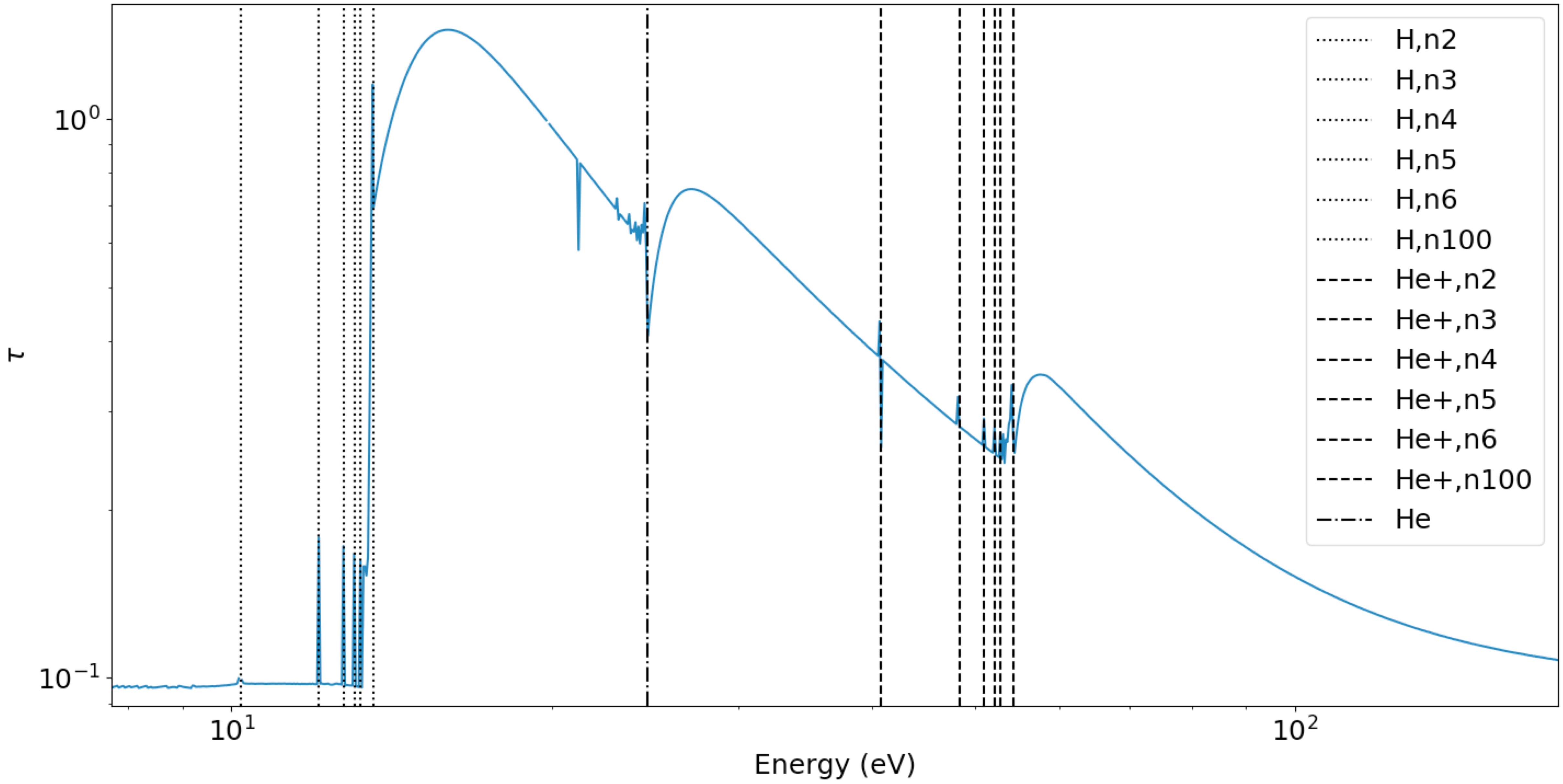
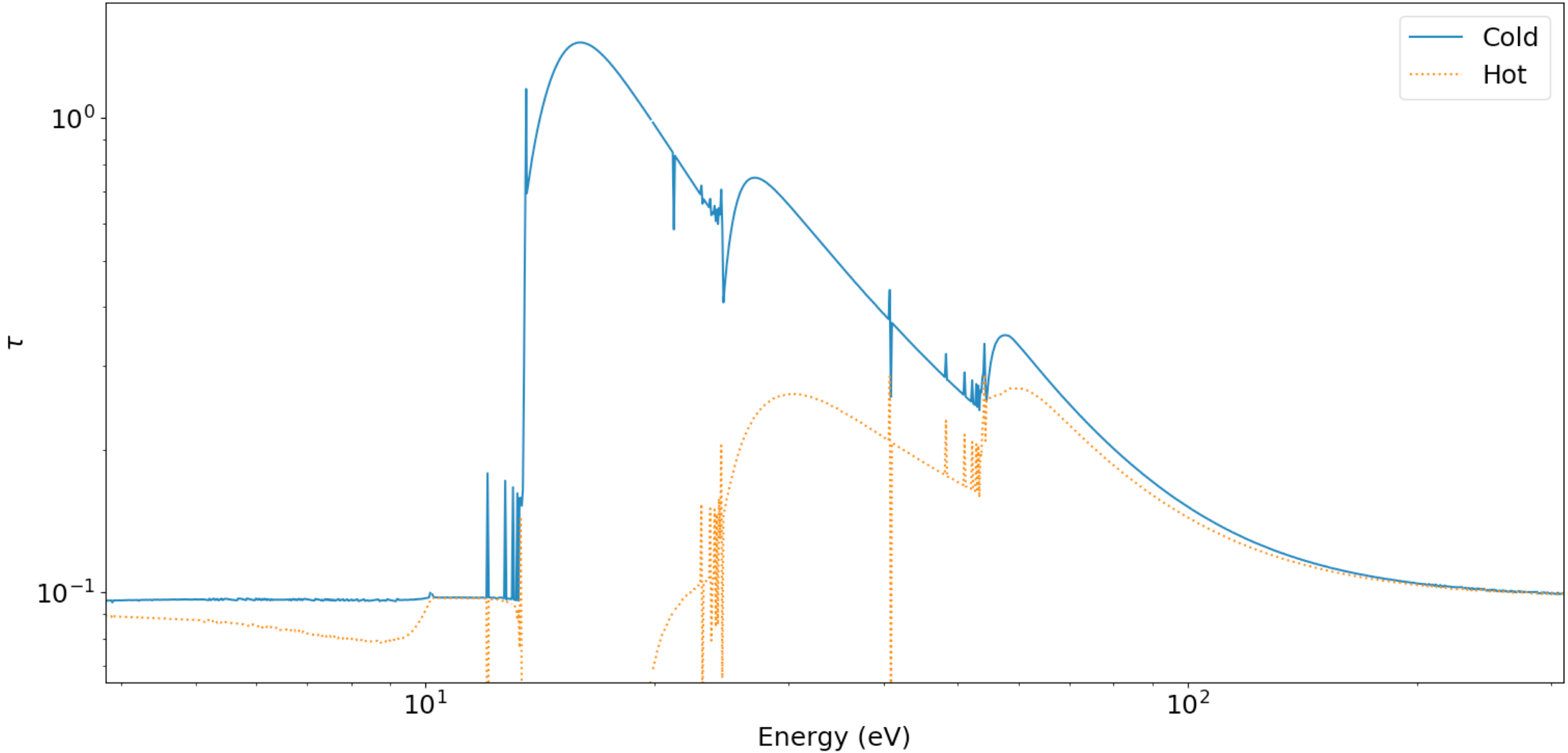


Figure 1: Fraction of ionization of Hydrogen as a function of temperature.



H,n2
H,n3
H,n4
H,n5
H,n6
H,n100
He+,n2
He+,n3
He+,n4
He+,n5
He+,n6
He+,n100
He
10^0
10^{-1}
τ
10^1
10^2
Energy (eV)



Cold
Hot
10^0
10^{-1}
τ
10^1
10^2
Energy (eV)

Problem 3 (Workshop): Heating and Cooling

Aim: Study the heating (part A) and cooling (part B) of a gas cell

Set up (part A): Heating of H cloud

```
table power law -1 1 20.0 //set up a power law
intensity -3 vary //specifies intensity of ionizing radiation
grid -6 -2 1  //define the grid to vary intensity between -6 and -2
hden -5       // H density of 1e-5 cc
abundances "primordial.abn" //primordial mixture
abundances all -20  //keep only hydrogen
constant temperature 5e3 //do not solve for equilibrium temperature
set dr 0      // set zone thickness of 1 cm
stop zone 1  // do only one zone
iterate to convergence //iterate
save grid last "heating.grd" no hash //save grid info
save heating last "heating.heat" no hash //save heating
save cooling last "heating.cool" no hash //save cooling
save overwiew last "heating.ovr" no hash //save overview



```

Tasks (Part A):

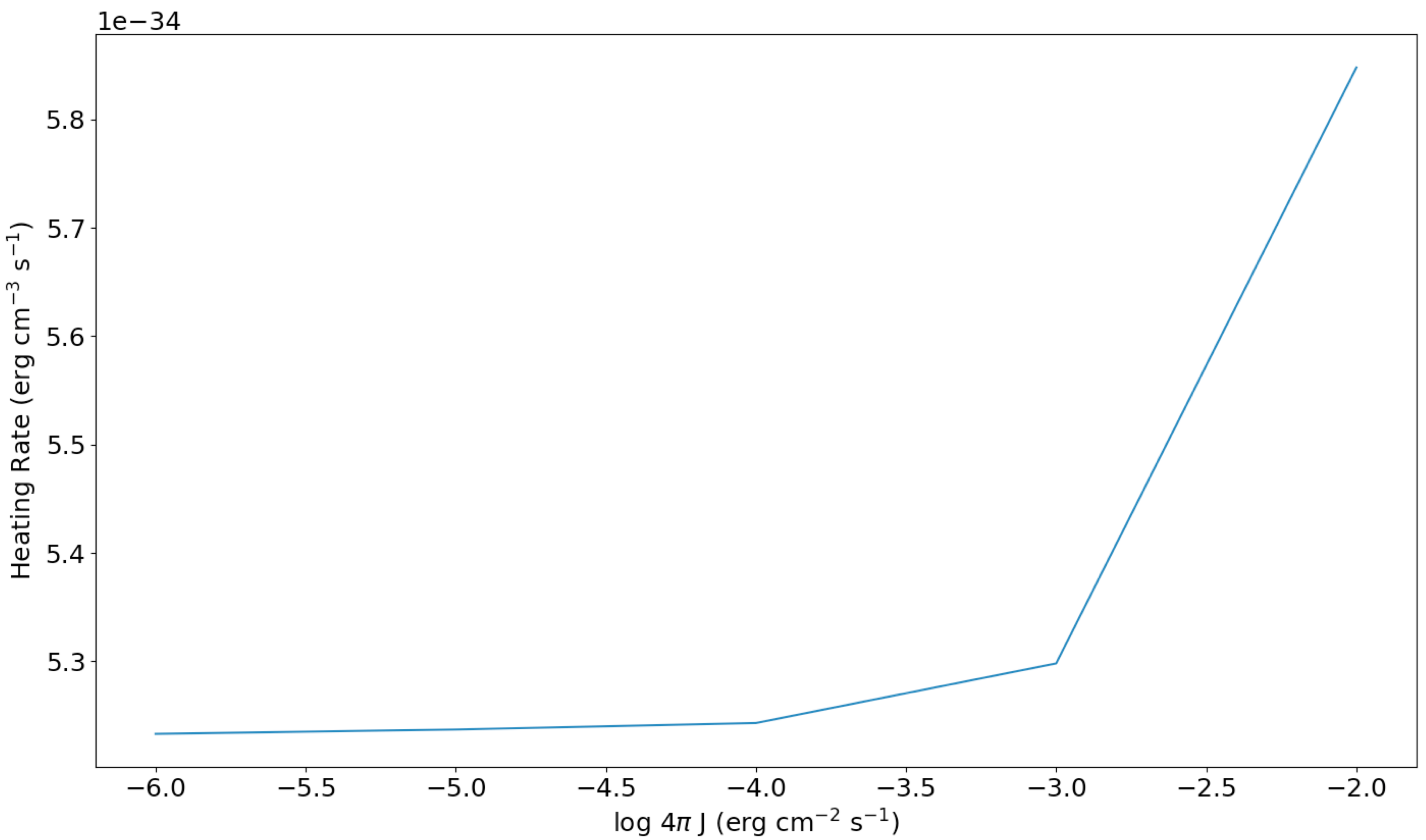
1. Plot the heating rate as a function of intensity. Explain your results.
2. Repeat your calculation by varying the power law index. Explain your results.

Set up (part B): Cooling as a function of chemical composition

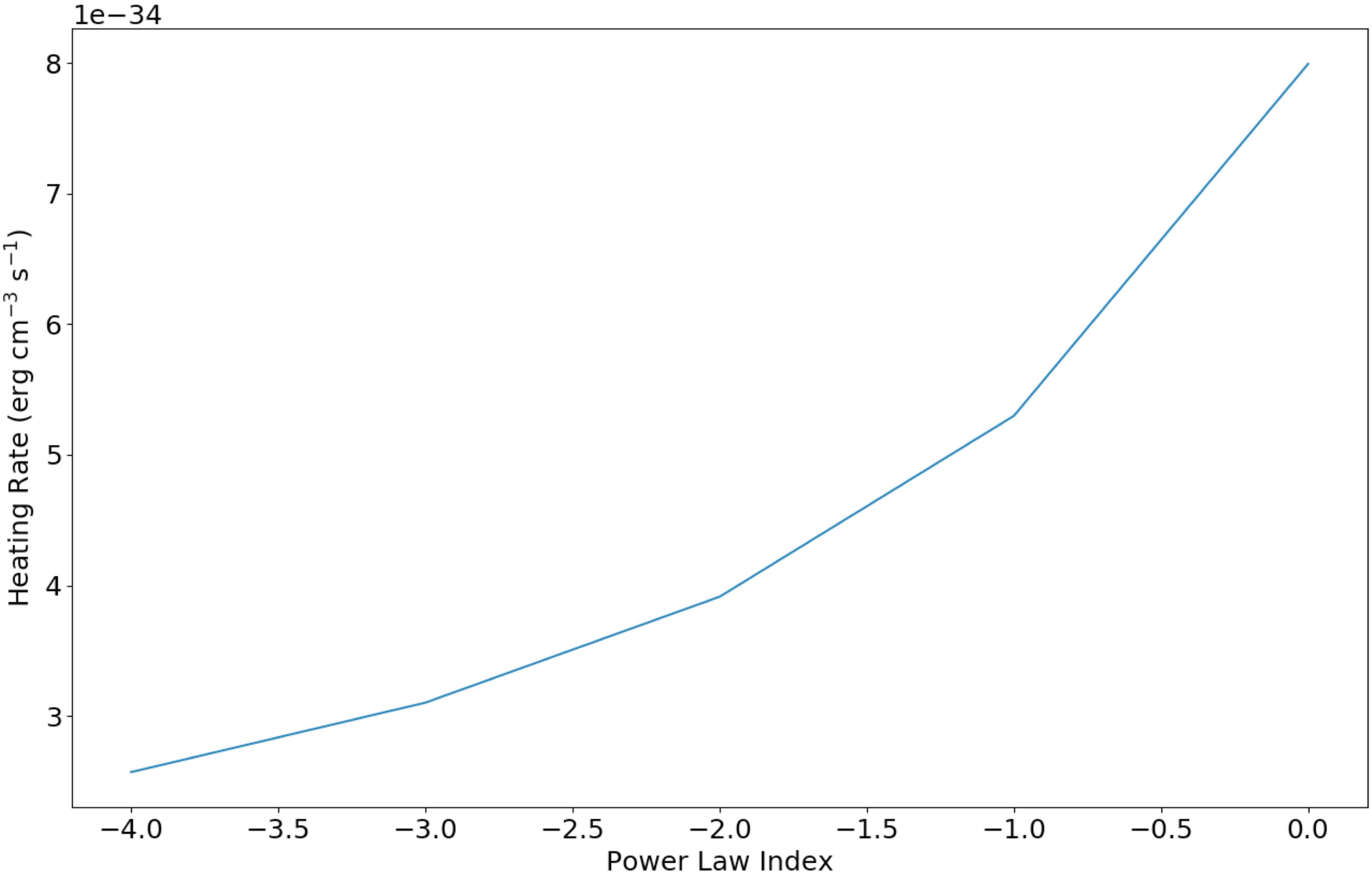
Start with a setup similar to part A, and build a grid of calculations at constant temperature using the "coronal" command between log T = 4-10 K. Consider a gas density of 1 cc.

Tasks (Part B):

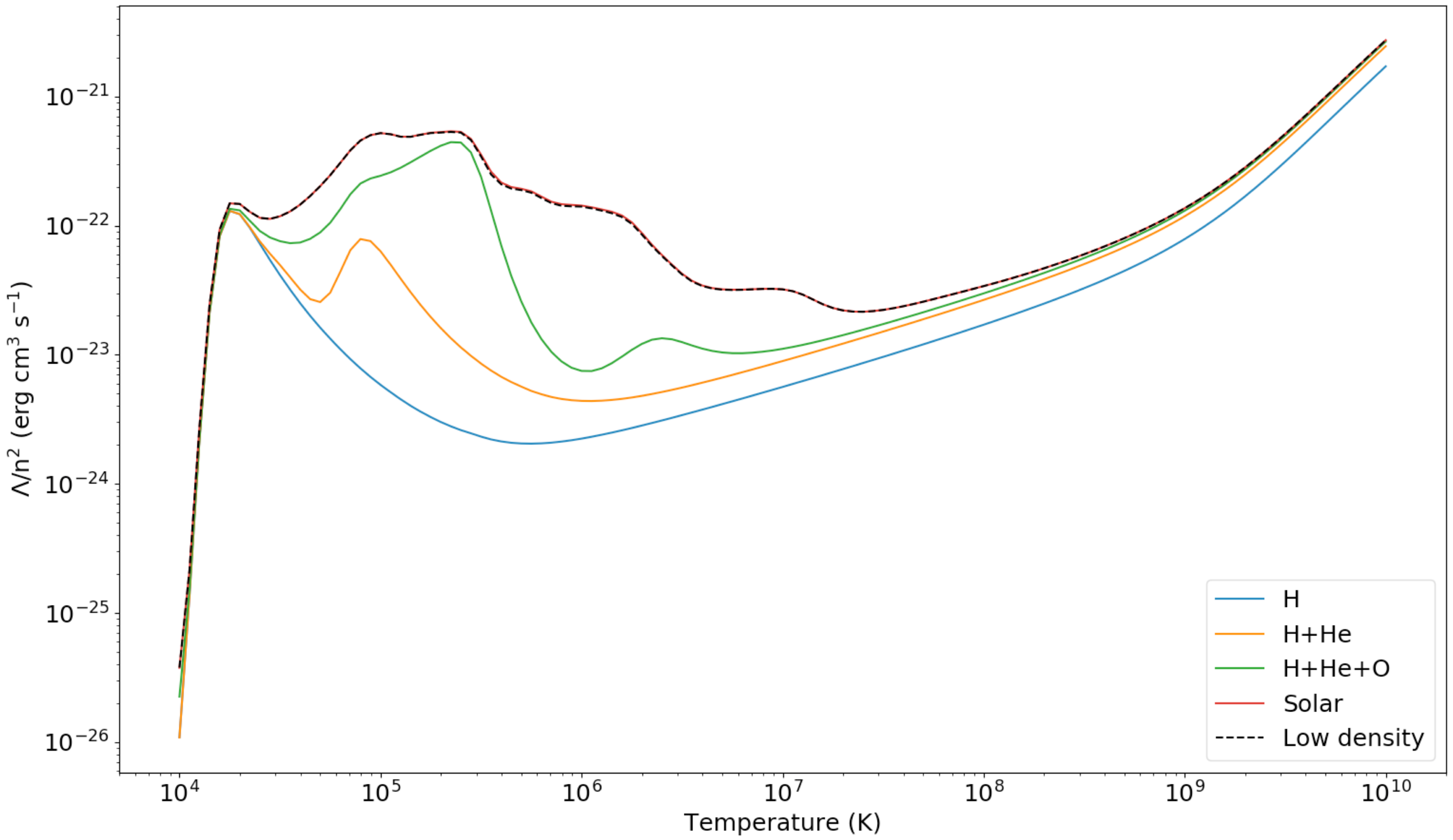
1. Compute the cooling function for H only
2. Repeat your calculation for H+He, H+He+O, and solar abundance
3. What is the effect of density? What's happening at 10^9 K?



1e−34
Heating Rate (erg cm−3 s−1)
5.3
5.4
5.5
5.6
5.7
5.8
−6.0
−5.5
−5.0
−4.5
−4.0
−3.5
−3.0
−2.5
−2.0
log 4π J (erg cm−2 s−1)



1e−34
8
7
6
5
4
3
Heating Rate (erg cm^{-3} s^{-1})
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
Power Law Index



Λ/n^2 (erg cm^3 s^{-1})
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Temperature (K)
H
H+He
H+He+O
Solar
Low density

Homework

Choose 1 problem from the following 3 (marked out of 10), and submit a short write-up by January 13.

Problem 1: The physics of HII regions

Problem 2: Temperature/density sensitive lines

Problem 3: The ionization stages of elements in the IGM/CGM/ISM

A write up should include: the .in files, plots of the results, and appropriate discussion of the results.

Problem 1: The physics of HII regions

1. Model an HII region of an O star within a cloud of H+He. [3 marks for sensible setup]

2. Plot the ion fractions as a function of radius and compare the HII region size with the Stromgren radius. Compare the ion fractions with the temperature. [2 marks]

3. Compare the relative size of the HII and HeII region as a function of the star temperature. Explain your result. [3 marks]

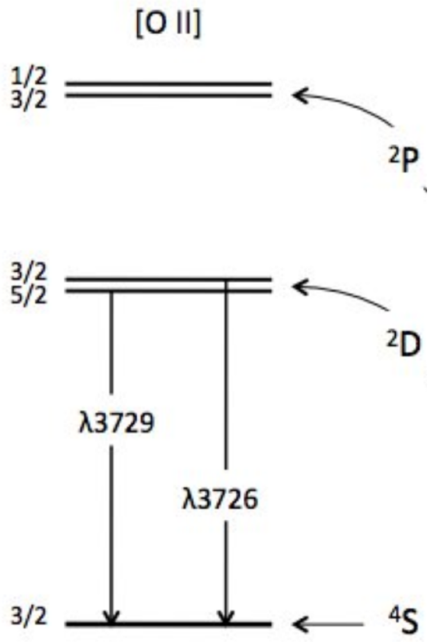
4. Show that the flux of the Hα emission line is directly proportional to the flux of ionising photons and verify this proportionality with cloudy. Compare with the star formation calibration of Kennicutt 1998 (AARA, eq 2) [2 marks]

Hint: for an HII region, you need to consider the “sphere” case.
See /cosma/local/c17.00/tsuite/auto/hii_*.in for examples of input files

Problem 2: Temperature/density sensitive lines

1. Using cloudy, study the ratio of [OIII] line intensities (λ4959+λ5007)/λ4363 as a function of temperature and density. Explain your results [5 marks, 2 of which for a sensible setup]

2. Following the derivation for [OIII], show that the ratio of the [OII] line intensities λ3729/λ3726 (see the diagram below) depends on the radiative transition probabilities A(λ 3729) and A(λ 3726) only at the limit of high density [3 marks]



3. Using cloudy, tabulate the [OII] line ratio as a function of density and temperature. Explain your results. [2 marks]

Hint: See page 216 of Hazy1.pdf for an example of the setup

Problem 3: The ionization stages of elements in the IGM/CGM/ISM

1. Using cloudy, compute the ionization stages of a cloud composed of H+He+O that is 100 pc in size and:
   i. in the IGM and is illuminated by the UVB at z~3
   ii. in the halo of a galaxy and is illuminated by an effective radiation field that is five times the intensity of the UVB at z~3
   iii. in the diffuse ISM of a galaxy and is illuminated by the local interstellar radiation field characterized by an escape fraction of ionizing radiation of 10%

[6 marks, 2 for each part with a sensible setup]

2. Compute the absorption profile of the HI Lya, OI 1039A, and OVI 1037A transitions for each case. [4 marks]

Hint: See Problem 2 for an example of the setup. For point iii), check the "table ism" command in the manual.