

Saas Fee Winterschool 2013

Hands-on session for lecture by Nick Gnedin

1 Radiative cooling in the IGM

(purely analytical)

Consider two equations governing the ionization and thermal state of the IGM after reionization with the radiative cooling term included:

$$\frac{d}{dt}x = -x\Gamma + R(T)n_{\text{H}}(1-x)^2 \quad (1)$$

$$\frac{3}{2}\frac{d}{dt}((2-x)k_{\text{B}}T) = x\Gamma\langle\Delta E\rangle - \Lambda(T)n_{\text{H}}(1-x)^2 \quad (2)$$

with

$$\Lambda(T) = \frac{3}{4}k_{\text{B}}TR(T).$$

The initial conditions have been discussed in the lecture: $T = \langle\Delta E\rangle/(3k_{\text{B}})$ and $x = x_{\text{eq}}$ at $t = t_{\text{rei}}$. For simplicity, consider a region at the exactly mean density of the universe,

$$n_{\text{H}} = n_{\text{H},0}a^{-3}$$

and assume matter dominance, $a(t) \propto t^{2/3}$.

Compare your solution to the case with $\Lambda(T)$ neglected.

2 Cooling (and heating) functions of rarefied photoionized gas

(requires Cloudy)

Download file `chfun.tar/gz` from the school webpage. Unzip and untar the file inside the Cloudy installation directory (`c10.00`). It will create a sub-directory `chfun`. Change to that subdirectory and run `make`. That should create an executable `chfun.exe`. Run it to make sure everything compiles correctly, the results should be

| | | | | |
|------|-----|-----------|------------------|------------------|
| nH=1 | Z=1 | T=10: | Cfun=1.07617e-26 | Hfun=2.44403e-23 |
| nH=1 | Z=1 | T=100: | Cfun=3.00754e-25 | Hfun=1.11542e-23 |
| nH=1 | Z=1 | T=1000: | Cfun=1.28274e-24 | Hfun=3.61474e-24 |
| nH=1 | Z=1 | T=10000: | Cfun=3.12827e-24 | Hfun=8.85994e-25 |
| nH=1 | Z=1 | T=100000: | Cfun=2.62157e-22 | Hfun=3.74696e-27 |
| nH=1 | Z=1 | T=1e+06: | Cfun=7.79562e-23 | Hfun=6.34524e-29 |
| nH=1 | Z=1 | T=1e+07: | Cfun=1.57009e-23 | Hfun=3.49724e-30 |
| nH=1 | Z=1 | T=1e+08: | Cfun=1.66913e-23 | Hfun=6.59414e-31 |

Now open the main file `main.cpp`. There you will see a simple loop calling the driver function `RunCloudy(...)` from `runcloudy.cpp`. If you want to see how Cloudy can be driven from your code, take a look at that file, but for this project you can use it as a black box.

In order to compute the cooling and heating functions, you need to set the density `nH`, gas metallicity `Z`, gas temperature `T` and the radiation field. The radiation field is set by the Cloudy "Table" command in the string form:

```
//sprintf(radfield,"Table HM05 factor=%lg",factor);
sprintf(radfield,"Table ism factor=%lg",factor);
```

(the one set in `main.cpp` is the ISM field, but you can also set the Haardt-Madau model for the Cosmic Ionizing Background or many other shapes for the radiation spectrum supported by Cloudy (but for that you need to dive into Cloudy documentation).

For this exercise vary the strength of the radiation field (parameter `factor`) by several orders of magnitude up and down and plot the cooling and heating functions for a range of temperatures and a couple of values of gas metallicity (say, solar `Z=1` and low metallicity `Z=0.1`).

3 Stellar feedback

(plotting only)

Download the file `muv.tar.gz` from the school web page. The tarball contains these files:

```
-rwxr-xr-x Home/None      47084 2013-03-05 17:58 muv0900.res
-rwxr-xr-x Home/None      47084 2013-03-05 17:58 muv1000.res
-rwxr-xr-x Home/None      47084 2013-03-05 17:58 muv1500.res
drwxr-xr-x Home/None         0 2013-03-05 21:23 nick/
-rwxr-xr-x Home/None      6148 2013-03-05 17:59 nick/.DS_Store
-rwxr-xr-x Home/None        71 2013-03-05 17:59 nick/.smhist
-rwxr-xr-x Home/None     1392 2013-03-05 17:59 nick/sb.sm
-rwxr-xr-x Home/None    57715 2013-03-05 17:59 nick/sb99.ps
drwxr-xr-x Home/None         0 2013-03-05 21:23 nick/Z0020/
-rwxr-xr-x Home/None      6148 2013-03-05 17:59 nick/Z0020/.DS_Store
-rwxr-xr-x Home/None    240518 2013-03-05 17:59 nick/Z0020/standard.power1
-rwxr-xr-x Home/None   144367 2013-03-05 17:59 nick/Z0020/standard.quantal
-rwxr-xr-x Home/None    250515 2013-03-05 17:59 nick/Z0020/standard.snr1
```

Files in the sub-directory `nick` have been used to make the plot I (will) present in the last lecture. To plot the bolometric luminosity from a stellar population, read columns 1 and 8 from the file `nick/Z0020/standard.quantal`; column 1 is the time in years, column 8 is \log_{10} of the bolometric luminosity in $\text{ergs/s}/(1e6 \text{ Msun})$ - subtract from it $\log_{10}(3.86e39)$ to get the units I used - L_{\odot}/M_{\odot} . The supernova energy injection comes from columns 1 and 3 of file `nick/Z0020/standard.snr1`, and wind power is in the file `nick/Z0020/standard.power1`, columns 1 and 2.

Three files `muv*.res` contain results of running a spectral synthesis code FSPS written by Charlie Conroy. They contain fluxes from stellar populations at wavelengths 900, 100, and 1500 angstroms (ionizing luminosity, the LW band, and the standard UV band). File formats are identical:

```

                22          94
122 0.200E-03 0.300E-03 0.400E-03 0.500E-03 0.600E-03 0.800E-03 ...
5.500 0.250E-12 0.244E-12 0.242E-12 0.238E-12 0.242E-12 0.233E-12 ...

```

The first line is the table size - the table contains 22 columns and 94 rows. Each column is a different metallicity, each row is a different time. The second line in the file contains an integer number you should ignore (122 in the example above) and then 22 metallicity values in absolute units (divide by 0.019 to get metallicities in solar units). All subsequent lines contain the data (like the third line in the example above): in each row the first number is the $\log_{10}(\text{time})$ in years, the next 22 numbers are stellar fluxes per log frequency per unit mass (i.e. $\nu L_{\nu}/M$) in units of L_{\odot}/M_{\odot} .

As an exercise, plot the stellar bolometric luminosity, ionizing luminosity, and supernova energy input as a function of time for, say, solar metallicity (or your favorite metallicity value). Then compute what fraction of ionizing luminosity is emitted before the first supernova explodes.

If one uses supernovae to clear out dense absorbing gas and to allow ionizing radiation to escape from the star forming region and the parent galaxy, what is a reasonable upper limit on the escape fraction - the fraction of the total ionizing luminosity emitted by stars that manages to escape from the parent galaxy?