Chemical Evolution of the Universe
Problem sheet 6

Let us study the evolution of the structure of a star with $M = 2.5\, M_{\odot}$. To this end, please visit `http://www.astro.wisc.edu/~townsend/static.php?ref=ez-web`. This web page provides an online interface to the EZ stellar evolution code. Read the information provided and then, in the section “Submit a Calculation”, enter an initial mass of 2.5, click “Create Detailed Structure Files?” and provide your email address. Leave the other parameters unchanged (Metallicity = 0.02, Maximum Age = Maximum Number of Steps = 0), and click “Submit”. The format of these files is explained at the above web page in the section “Output File Formats”. After a few minutes you will receive an email with a link to a zip file that will contain the result of the calculation. Download the file and unzip it. You will find a total of 834 files, one summary file and 833 detailed structure files, one for each time-step of the simulation.
The summary file provides a number of the star's parameters, such as its luminosity or radius, as a function of the step number of the simulation, or equivalently, of its age. The detailed structure files contain, for each step number (or age), the radial profiles of a number of the star's parameters. In other words, these parameters are listed as a function of radius, or equivalently, of the mass enclosed within this radius.
In the following we will analyse these files in order to understand a few aspects of this star's evolution. For this you will need to be able to make plots of some of the contents of some of the files above. If you do not already know how to make plots, then please install and learn how to use gnuplot (`http://www.gnuplot.info/`), which comes with excellent documentation. As a quick start, in order to simultaneously plot the evolution of the logarithm of the surface and central temperatures as a function of age, execute:

```
set logscale y
plot "summary.txt" using ($2):(10**$7) , "summary.txt" using ($2):(10**$6) with lines
```

1. First, let's get our bearings. Plot $\log R$ versus step number and age.
   (a) Why do these plots look so different?
   (b) Are the steps equally spaced in time? To answer this question, plot age versus step number.
   (c) Judging from these plots, at what age and step number does the star leave the main sequence?

2 points

2. Now plot the logarithm of the star's luminosity versus the logarithm of its surface temperature, with temperature increasing to the left. This will show you the evolution of the star in the Hertzsprung-Russel Diagram (HRD), beginning on the zero-age main sequence.
   (a) Mark the location on the HRD of the star's departure form the main sequence as determined above. What exactly happens here? To answer this question, plot the power per unit mass from the pp chain and the CNO cycle (i.e. of the H-burning reactions) as a function of radius or M_r for a few steps around this time. Describe in words what happens here.
   (b) Following the path of the star in the HRD, you will find a very narrow “spike” with its tip at $\log T \approx 3.64$ and $\log L \approx 2.6$. What is the part of the spike called that leads toward the tip? At what age and step number does the star arrive at the tip of the spike? What exactly happens there? To answer this question follow the same procedure as above. (Hint: you may also wish to consider the power per unit mass from the triple α reaction.) Again, describe in words what happens here.

3 points

3. Plot the evolution of the mass fractions of C, N and O at the surface of the star as a function of time and step number. (Careful: the detailed structure files are ordered from the surface to the centre.) Let's find out what's going on here.
   (a) Compare the step number of the change of the mass fractions to the one found in the previous problem. So which nuclear reaction is the only one that can possibly be responsible for the observed change?

(b) But this nuclear reaction only ever occurs deep inside the star. So how are any changes to the mass fractions of C, N and O produced by this reaction propagated to the star's surface?

(c) If convection is responsible for transporting the products of nuclear reactions in the core to the surface of the star, then at some point during the evolution of the star the convective zone must have extended from the surface all the way down at least to the outskirts of the core.

Whether the energy transport across a given mass shell at radius r happens radiatively or by convection is determined by the relative values of the radiative and adiabatic temperature gradients. The star is convective at r if the adiabatic temperature gradient at r is smaller than the radiative temperature gradient at r.

Plot the profiles of adiabatic and radiative temperature gradients for a few steps around the step number you identified in (a). Also plot the profiles of the C, N and O mass fractions at the same step numbers. What do you find? Does the convection zone reach down into the star far enough in order to be able to mix the products of the nuclear reactions into the upper layers of the star?

7 points