Senior astrophysics Lab 3: Evolution of a massive star

Name:

Checkpoints due: Friday 20 April 2018

1 Introduction

Last lab, we followed the evolution of a $1 M_\odot$ star from the birth of the star (time $t = 0$), through the main-sequence phase and up the giant branch. This time, we are going to use *Window to the Stars* (WTTS) again to model the evolution of a massive star.

Follow the instructions from last week's lab to log in to the Linux server; then move to the directory you created last week and start the program:

```
cd WTTS
wtts &
```

2 Exercise 1: Massive star model

Evolve a high mass model, $M = 15\,M_\odot$ (choose the $14.96\,M_\odot$ option). Set INIT_RUN.KPT to 2000 (the code will actually stop after about 1620 steps).

Save the model once it has completed; choose a sensible name like `15Msun`. You will need to re-load this later in the exercise.

Q1 Using the *Structure* tab, plot the log central temperature vs age.

Q2 Indicate the region of the plot where the star is on the main sequence. How does the core temperature of this star at the mid-point of its main-sequence lifetime compare with the core temperature you found for the Sun last lab?

Q3 Now make a plot of the central abundances of the different products of nuclear burning, as a function of time (age).

Q4 Relate the features in your first diagram to the different burning stages you can see in your second diagram. At what age does the central hydrogen abundance go to zero? Mark this age (accurately!) on your sketch in Q2.

Q5 Restrict your plot to the time before helium burning starts. What is the sum $C + N + O$? Why is this sum a constant?

▶ **CP1**

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3 Exercise 2: Convection

Now we are going to look at the *Kippenhahn* tab. A Kippenhahn diagram is a plot of time (or model number) on the x axis, mass coordinate on the y axis and a colour or shading to indicate convective regions in the rest of the plot. This is a good way of visualising the **changes** in the interior structure of the star as a function of time.

Recall that in lectures, we briefly discussed convection. The condition for stability depends on the temperature gradient; the condition for stability is

$$\left(\frac{dT}{dr}\right)_{\text{star}} < \left(\frac{dT}{dr}\right)_{\text{adiabatic}} \tag{1}$$

If the temperature gradient in the star is **steeper** than the temperature gradient when an element is moved adiabatically, then this leads to the onset of convection. In WTTS, the condition for convection to occur is written

$$\nabla_{\text{rad}} - \nabla_{\text{ad}} > 0 \tag{2}$$

Load the $1M_\odot$ model that you created last lab[1], and answer the following questions.

- Select the *Kippenhahn* tab.
- You should see the usual *Star 1/2* selector, just leave this at Star 1.
- You then have the x, y, z axis settings (z is the colour surface which will be plotted, equivalent to the convective regions in the canonical Kippenhahn diagram).
- You can choose the variables, and whether to plot them in a linear, log or 10^x fashion, from the drop down menus. The variables which are available to you are the same as those in the Internals tab, so you should be familiar with them.
- Ranges can be set in the boxes (autoscaling is again marked with an asterisk *).
- The *Palette* section allows you to change the colours.
- Next are the *Show...* buttons. These are only useful if your y coordinate is the mass M. They allow you to plot mass boundaries (the surface, core etc.), convective boundaries and nuclear burning zones. These are really for the expert user, but perhaps you will find them useful.
- The *Replot* button is where the action happens. Unlike all the other plots in WTTS, the Kippenhahn diagram does not plot itself when you change something. The reasoning behind this is that the replot may take a very long time, so if a continuous replot was to happen it would slow you and your machine to a crawl. You can also replot by pressing the r key.

Now let's make a traditional Kippenhahn plot.

- Select *Age* for the x axis, M for the y axis and *Convection* for the z axis. Select *Log10* for the z axis. The special variable *Convection*, given by equation 1, is actually defined in WTTS as $\max\left[\nabla_{\text{rad}} - \nabla_{\text{ad}}, 10^{-30}\right]$, so is positive when there is convection, and tiny (but positive) when there is not. Taking the log means we show only the convective regions. Hit *Replot*.
- You will see mostly black, which corresponds to -30 in the colour key. This is because $\nabla_{\text{rad}} - \nabla_{\text{ad}}$ is actually negative in these regions and the logarithm of a negative number is not possible (in this context at least!). To cope with this, WTTS sets $\nabla_{\text{rad}} - \nabla_{\text{ad}}$ to something very small but positive (in this case 10^{-30} which logs to -30). You can get around the problem by setting the z range minimum to 0. Hit *Replot*. You should see a coloured band across the top.

[1] If you didn't save the model last week, you can download a pre-made model from eLearning.

Remove the range setting, set the resolution to 100% and press *Replot*.

Q1 Sketch the plot you have just made, showing the location where convection is occurring.

Q2 Explain what you are plotting on the y axis: what does it mean to use M as a coordinate? Why is this sometimes more informative than using R? (Try it and see the difference!)

Q3 What is the depth of the convective envelope in the Sun? (You worked out which model/age corresponds to the Sun in the previous lab exercise). Does it vary over most of its lifetime?

▶ **CP2**

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4 Exercise 3: More Kippenhahn diagrams

In WTTS the idea of a Kippenhahn diagram is extended. Instead of just plotting the convective regions, you are allowed to plot **any** variables on the x and y axes, and any variable for the colour (mapped surface) plot. This enables us to visualise the way that different properties of the star's structure change during the evolution.

Q1 Still on the Kippenhahn tab, and using the $1\,M_\odot$ model again, plot age on the x-axis, mass on the y-axis and H (hydrogen) on the z-axis. Explain what you see.

Q2 Now plot *Age*, *M* and *E_nuc* (the last in log)[2]. This shows the regions where nuclear burning is taking place. What happens to the burning region when the core runs out of hydrogen? Try restricting the y range to show the detail better; change the z range as well (try setting the minimum value to 0). You might like to experiment to find a colour palette which makes the behaviour clear; I like the *White-Yellow-Red-Black* one.

Q3 Change *Age* to *Model number* and replot. Why is it easier to see the details of the transition from core to shell burning when plotting against Model number? Why is the Model number not simply linearly proportional to time?

Change *Model number* back to *Age* (recreating the plot from Q2) and save a copy of the image, by right clicking on the plot and selecting *Save as PNG*.

[2]Make sure you are using $E_{\rm nuc}$ (nuclear energy) not $E_{\rm nu}$ (energy in neutrinos)!

Now load your 15 $M_\odot$ model back in using the *Load/Save* tab.

Q4 Make the same plot as in Q2 for the massive star, and compare with the image you saved for the 1 $M_\odot$ star. Sketch the important features of both in the box below. Explain the differences that you see. How many burning regions can you identify? (Try plotting against model number again: this might makes things clearer. What do you notice about the time step in the final stages of your model?)

▶ **CP3**

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