2009
ASP3012

Stars Lab 4: Stellar Evolution with WTTS

1 Introduction

Welcome to the *Stellar Evolution with Window To The Stars* lab. In the following we will guide you through the process of making your own stellar models in a variety of scenarios. You will make models, analyse them, and at the same time learn a bit about how stars work. The software we will use is called *Window To The Stars*. It is a free user interface to a stellar evolution code called *TWIN*. You can find details of the code, installation instructions and a manual at the website `http://www.astro.ulb.ac.be/~izzard/window/`. Here we will give a brief introduction.

1.1 Window To The Stars

Window To The Stars (*WTTS*) was developed in 2006 by Dr Rob Izzard and Dr Evert Glebbeek to provide an easy way to use a complicated tool - a stellar evolution modelling program. The physics of stellar evolution is difficult enough, without having to worry about computational details. *WTTS* runs on PCs under Windows and Linux, and on Macs with OSX. It uses only free software and is all open source.

Figure 1: The authors of the codes: Dr Rob Izzard (left), Dr Evert Glebbeek (middle) and Dr Peter Eggleton (right). They all come from good families, but over the years they have developed ways about them that are . . . well . . . just not right.

It is installed on the computers you will use but you are free to install it on your own machine if you like. You should go to the *WTTS* website and follow the instructions for installation. If you have problems, email the authors using the address provided at the website. (Tell them you are a student of Lattanzio's at Monash and they will help - we work closely with them on research problems and they will help you or they will not get any research money from me!)

1.2 TWIN

WTTS is an interface to the program *TWIN*. This is the single and binary stellar evolution code of Dr Peter Eggleton and collaborators. Eggleton spent most of his career at the Institute of Astronomy at Cambridge University. He currently works at the Lawrence Livermore National Laboratory in the USA.

1.3 Running *WTTS*

In each section that follows it is assumed that you are already running *WTTS* according to the instructions given on the website. Usually you just type *wtts*. Note that *WTTS* will store files (many large files!) in the directory from which you run it so please make sure you have sufficient disk space in the current directory. If in doubt, make a new directory and run *WTTS* from there.

1.4 Familiarity with WTTS

Please read the section *Using Window To The Stars* in the *WTTS* manual (available from the website as well as MUSO and my ASP3012 Stars website) before starting this lab. You do not have to remember the details but it would be very useful for you to get an idea of what is going on and how it works before you dive in.

2 Main Sequence of Sun-like model: $M = 1\,\mathrm{M}_{\odot}$, $Z = 0.02$

The Sun is the nearest star to the Earth and we shall start by trying to make a model of it. We cannot observe the H or He content of the Sun, as there are no suitable spectral lines available. We do know the "metal" content however. That is about 2% or $Z = 0.02$. We will make a model of a star the same mass as the Sun, and we will take $Y = 0.28$ and $X = 0.70$. This model comes with the software so we can load it very easily!

First we must make a sequence of $1\,\mathrm{M}_{\odot}$ models starting from the birth of the star (time $t = 0$), through the main-sequence phase and toward the giant branch.

1. Start *WTTS.*
2. We wish to start from a *Zero-Age Main Sequence (ZAMS)* model of a star similar to Sun. It is thought the Sun formed (its *"Zero Age"*) about $4 \times 10^9 \equiv 4\,\mathrm{Gyr}$ ago from some kind of spinning gas cloud. Unfortunately, we cannot model such formation with *WTTS* – indeed nobody really knows how it happened and the best models require huge 3D hydrodynamics models – but the product of the formation mechanism is just a hydrostatic $1\,\mathrm{M}_{\odot}$ burning ball of gas. *That* we can model with a stellar evolution code.
3. In the *Options* tab go to the *Option Control* section and press *Reset from defaults*. This sets all the options to their default settings. We will mess about with the options later on.
4. Staying in the *Options* tab, select the button *From ZAMS Library*. To the right of this are three menus for Z (choose 0.02), M1 (choose 1) and M2 (choose anything). Of course we're only really using star 1 but TWIN crashes if star 2 isn't set to something!
5. In the *Convection and Thermohaline mixing* tab set CALP to 1.5; this is a convection parameter which is unknown. We will return to this later.
6. In the sub-tabs (marked *Operation Mode, Initial Conditions...*) find the *Operation Mode* tab. Make sure *INIT_RUN.ISB* is set to 1 (single star operation) and *INIT_RUN.KTW* is set to 1.
7. Set *INIT_RUN.KPT* to 750. This is the number of time-steps that *TWIN* will run for, in our case 750 is enough.
8. Click on the *Evolve* tab.
9. Click on *Clear Log Window* – this clears the log window of any previous data.
10. Click on *Evolve* and wait a few seconds. You will see the status bar change to *Calling Evolve Script* and then, hopefully, to something like *Evolving 27.21Mb ev (pid 4644)::23.08Mb*. This means that TWIN is running! The *27.21Mb* is the amount of memory *TWIN* is using, *pid 4644* is the process ID of the *TWIN* process (called *ev*) and *23.08Mb* is the amount of memory that *WTTS* is using. These are diagnostics, you probably should only pay attention to them if the numbers get very large, or if some red text appears to indicate something has gone wrong.
11. The status bar has two more lines, marked *Star 1* and *Star 2*. In our case we are not using *Star 2* so it is always marked *Pending...* - just ignore it. Star 1 shows the current model number, time, timestep, mass, metallicity, luminosity, effective temperature and radius. This is updated as the star evolves.
12. After a little while the screen will fill with some text. This is the log of what is going on. Most of it is just numbers, but it is useful to see what is happening (once you know what it means!). You do not need to understand this log, but note that if there is no log then something has gone wrong.
13. Click on *Update Log Window* – this refreshes the log. Sometimes it goes wrong and does not update properly so this is useful to check that everything is actually there.

14. Click on *Follow Log*. This option forces the log window to follow the bottom of the logfile, which is the newest text. This is the best way to follow the evolution of your star.

15. Wait for the sequence to finish, which it will do when it gets to 750 models (it may stop earlier if something goes wrong!)

16. If you wish to stop the evolution you can do so at any time by clicking on the *Terminate* button.

17. You will know when the evolution sequence is finished because the status bar will read (in red) *In Star 2: STAR12 no timesteps required*. This cryptic message just means it is done, you can move to section 2.1.

18. Now save your model sequence by going to the *Load/Save* Tab. Now click on *Save Model Set* and in the popup dialog box, enter a name such as your name or initials and `Sun1` or something to remind you that this is an approximate model for the Sun. You will be able to load this if the program crashes, and it will save re-running it from the start!

2.1 The Hertzsprung-Russell Diagram

The primary tool of stellar evolution is the *Hertzsprung-Russell diagram* (HRD). This is a graph with the *effective temperature* (T_{eff}) on the x axis and *stellar luminosity* on the y axis. (Both are presented after taking the base 10 logarithm.) We shall examine the HRD of the model sequence you just made.

1. Click on the *HRD* tab. In this tab you should see the HRD of your model sequence.

Q1 What is the initial temperature of the model? What is the maximum temperature it reaches?

2. Incidentally, in most of the graphical panes you can right click to save the graph as a postscript file. If this does not work, you can always take a screen grab and edit it later!

3. You can zoom in and out by manually setting the *X Range* and *Y Range* boxes. Try it! To have the ranges set automatically set the boxes to * (asterisk).

4. The *Stellar Colours* button activates a feature which tries to colour your HRD according to real stellar colours. You can turn this on or off as you please (and you can adjust the hue and brightness in the *Misc* tab; I found the best results for a Brightness of 150, Contrast of 2000 and Colour of 40).
   What colour is the star when you activate *Stellar Colours*?

5. You can label the curve in the HRD with one of many variables. The default is the *Age*, which is just the age of the star (in years). Note the labels along the curve. You can try selecting something else from the *Label With* drop-down menu. If you have too many/not enough labels, simply reduce/increase the *Label Spacing*.

Q2 Locate the point in the HRD corresponding to the same luminosity as our Sun has now. What is the approximate age? What is the effective temperature? Is this a good model for the Sun?

6. You can change the line width with the *Line Width* menu.

7. If you evolve a binary you can look at the other star, or both, with the *Star* menu.

2.2 Stellar Structure

While the HRD tells us something about how a star looks to an observer on the Earth, we are curious about what is happening in the interior. This is the *stellar structure*. In this section we will examine what is going on inside the star as a function of time.

1. Click on the *Structure* tab.
2. You will see some options on the left and an image panel on the right. By selecting some of the options you can display information about various stellar structure variables, such as the central temperature, chemical composition etc. as a function of (usually) time.
3. On the left, the first drop-down menu is the star number. Set this to *Star 1* because we are using single star models.
4. The next drop-down menu is the variable you wish to plot on the x axis. Set this to *Age*.
5. There are two sets of three buttons below this which allow you to modify what you plot on the x or y axis. You can either leave the data as it is (*Linear Y Axis*), take the base-10 logarithm (*Log Y Axis*) or plot 10^y (*10^Y Axis* - this is the opposite of *Log Y Axis*). The same rules apply to the x axis.
6. Next are the range boxes which allow you to specify the range of the plots. These allow you to zoom in and out. (Note that $*$ means that the program will scale the graph itself.)
7. Finally there is a long list of variables which you can plot on the y-axis. Try scrolling up and down to see how many there are.
8. Click on *Log Luminosity* and check the age when the star passes through the Sun's current luminosity.
9. Use the drop-down menu to change the x axis to *Model Number* so you can find the model number corresponding to the model with the current solar luminosity.

Q3a Which model has the Sun's luminosity? What is its age?

10. Click on *log Central Temperature*. This plots the temperature at the centre of the star vs the age of the star.

Q3b How hot is the centre of the star at age zero? What temperature does the star reach in the final model? What is the central temperature in the model most like our Sun?

11. The temperature rises until it reaches a plateau.
    At what age is the plateau reached? Approximately what is the central temperature at this time?
12. Click *log Central Temperature* to deselect it, and instead choose *log Central Density*.
    Is there a plateau in central density? What is the present-day central density of the sun?
13. Deselect *log Central Temperature*, now choose *Central abundance of H*. This shows you the abundance of hydrogen at the centre of the star by mass fraction. This means that if the abundance is 0.5, 50% of the mass is in hydrogen.
    What is the initial abundance of hydrogen? Why is the star not 100% hydrogen at the beginning of its life? What is the rest of the star made of at the beginning? Why does the hydrogen abundance drop with time? At what time is the central hydrogen abundance almost zero? Does this time look familiar to you?

Q3c How long does it take for the star to exhaust its central H supply? How does this affect the central temperature? Why?

Q3d Plot the radius vs time. When does the star pass through the current solar radius? Do you want to re-evaluate your rating of this model as an appropriate solar model? We can improve this by adjusting the convection parameter mentioned on page 2 (item 5: you might later want to try CALP=2.0).

14. Click on *Central abundance of He* but do *not* deselect the hydrogen abundance.
    What is the initial helium abundance? When and where was most of the helium made? Why does the helium abundance increase as a function of time? What is the final helium abundance? What is H+He at $t = 0, 2, 4, 6, 8, 10\,\mathrm{Gyr}$?

15. Deselect the hydrogen and helium abundances, instead select the central abundances of C, N and O (carbon-12, nitrogen-14 and oxygen-16) . You can see N and O but C is very hard to see, so click on *Log Y Axis*. Now that we have taken logarithms of the numbers we can see the changes much more easily.

Q4 What are the initial abundances of C, N and O? What is the sum of the initial abundances, i.e. C+N+O? Why does the C abundance drop so quickly at early times? (You may want to use log(time) on the x-axis.) What does C get turned into and which burning cycle is involved? What is the main product of this burning cycle? What happens to the oxygen abundance after $6\,\mathrm{Gyr}$? What does the oxygen get turned into and which burning cycle is involved? What is the product of this burning cycle? What is the sum C+N+O at $t = 0, 5, 10\,\mathrm{Gyr}$? Why is this (almost) constant? Why is it *not* quite constant?

16. You can use a different x coordinate from *Age*, for example *Model Number* (which increases non-linearly with the stellar age). *WTTS* is completely flexible in this sense.

17. Sometimes this leads to strange results, e.g. curves which are not monotonic.

18. A useful diagnostic is the *log central Temperature* vs *log Central Density* plot. Select this plot (with a *Linear X axis* and *Linear Y axis*).
    Which way does the curve evolve with time? What happens when the temperature reaches $\log T \sim 7.27$? Can you plot a graph to verify your hypothesis?

19. Experiment, make your own plots, can you explain everything you see?

2.3 Internal structure of the star

In the previous section we looked at the evolution of stellar structure from the point of view of a few special variables (e.g. central or surface temperature/density etc.). However, you will often want to know what is going on at any point in the star. In the *Internals* tab you can do this in a number of ways.

1. Click on *Internals*.

2. You will see a new tab window with some labels across the top, options on the left and a plot on the right.

3. The buttons across the top are the *Y Axis* (labelled *M*, *R*, *P* etc.). Hover your mouse pointer over each button to get a description of what it means. By selecting one or more of these you can choose what to plot on the y-axis.

4. On the left are many options, we will try a few. First, make sure *Star 1* is selected. This is the familiar selector you have seen before, but of course we still only have one stellar model.

5. You can make animations or still images. Click on *Still*.

6. There are several ways to visualise data, some are better than others. It depends on the range of the variables, etc. Click on *Line*.

7. Ignore *Frame* and *Speed* for now, they are controls for when we animate (later!).

8. Next you come to two drop-down menus. The first selects how we want to identify models, leave this at *Model Number*.

9. Second is the Abscissa (x axis) coordinate selector. Leave this at M (the mass coordinate) although of course you can change it to any coordinate you like (with strange results if the coordinate is not single valued!).

10. Next are the range boxes for the x and y axes. You can also click on the *Log 10 ...* buttons to take base 10 logarithms.

11. Now we come to the useful part. In order to see inside the star we have to look at a stellar model, which is really a snapshot of the stellar history. In our case we made 750 models, which are labelled from 2 to 751. You can select which of these models you would like to plot from the scroll box which lists them. You can select more than one. If you click on a model, hold shift, and click on another you can select a range. Try it.

12. The buttons marked *C*, *1*, *2*, etc. allow you to select models automatically. *C* clears the list, *1* selects them all, *2* selects every 2 models, and so on. The vertical bar | (which means *or*) inverts the selection. Experiment with these.

13. The *Latest* model always points to the final model in the evolution run. In our case this is number 751.

14. Press *C* to clear the list. Select *Latest* and model number 2 from the list (these are the first and last models).

15. Because you have not selected anything from the *Y axis* buttons, you will see nothing (*No Image* will be in the display). So, go ahead and press the *T* (temperature) button from the *Y Axis* buttons at the top. Make sure the Abscissa menu is set to *Abscissa: M*.

16. You now see two curves, one is the temperature as a function of mass for model 2 and one is for model 751. You can see that the star has become hotter at the centre and cooler at the surface.

17. Press *C* to clear the list, and now press *10* to select every 10th model. The graph shows 75 curves simultaneously, which is not at all easy to understand! (It might help to use *log* of the ordinate and to set the lower *Ordinate Range* to 6.)

18. It might be better to have fewer graphs. Press *C* to clear the list, and then press *25* to select every 25th model. The graph shows 30 curves which is a little easier to digest.

19. To help understand these graphs you can animate the curves. Press *Animate*. Set *Speed* to 11 to make the animation as fast as possible. *WTTS* will draw each of the 28 curves in its own window – this takes some time – and as it does so you should see the *Frame* number increase. Eventually all the curves will be drawn and the animation will loop. Try changing the *Speed* – a value of 11 is as fast as your machine can do it (you can make it faster by using PNG instead of Postscript images, which you can select in the *Misc* tab). You might want to change the maximum *Ordinate Range* to 7.5 so that the graph does not rescale during the animation.

20. Set the *Speed* to 0 and try manually scrolling through the different frames with the *Frame* button.

21. Ignore the *Sphere* and *Slice* options – these did once work but are currently buggy.

22. Finally, there are 20 buttons above the plot. Normally you work in plot 0 but you can actually have 20 simultaneous plots. Try choosing a different number, make a new plot and then try again.

23. Now press *C* to clear the list, set the *Ordinate range* to automatic (put an asterisk * in both boxes) and de-select *T* in the *Y Axis* buttons.

Q5 By making movies or still pictures in the *Internals* tab, answer the following questions:

a. The plot of log(density) vs mass shows what appears to be a point of inflexion near $m = 0.2M_{\odot}$. What is happening there?

b. Plot $\nabla_{rad} - \nabla_{ad}$ (with appropriate limits) to determine where the convective regions are. How do these vary with time?

c. The plateau on temperature indicates an isothermal core. Why does that arise? How much luminosity is generated in this core? By what?

d. Where and when are the neutrino losses important? (look at ϵ_{ν})

e. Look at the C, N and O abundances. What is happening near the end? Verify your answer by looking at the earlier answers!

We will now look at what this star looks like *today*.

1. In section 2.1 you noted the model number of our star at the age corresponding to the Sun. Find this model in the list and select it.
2. Plot luminosity L vs mass coordinate M. Select the *Ordinate range* to be 0 to 0.7 and the *Abscissa* range to be 0 to 1.0.
   What is the luminosity at the centre? What is the luminosity at the surface? What should it be for a solar model? What is the luminosity at $M = 0.5$?
3. Plot luminosity L vs radius R (select *Abscissa: R*)
   What is the radius at the centre? What is the radius at the surface? What should it be for a solar model?
4. Deselect R, choose *Abscissa M*, reset the *Ordinate range* (to * and *), select *Log 10 Ordinate* and press the *E_nuc* button.
   What is *E_nuc*? Why is it concentrated in the centre? (Hint: try changing the *Abscissa* to T or *rho*).
5. Deselect everything. Plot *Grad_rad-Grad_ad* ($\nabla_{\rm rad} - \nabla_{\rm ad}$) as a function of M – this measures the convection in the star (use the *log* buttons if you need to). Where it is positive there is convection, such as near the surface.

Q6 Observations of pulsations in the Sun lead to the claim that the outer 30% of the sun is convective. Our model is not a very accurate Sun, but does this plot support this view? If not, what do you think is meant by the "outer 30%" and can you make a plot to confirm this?

Q7 Change the abscissa from M to *opacity*. You probably need to log both axes. What is the relationship between $\nabla_{\rm rad} - \nabla_{\rm ad}$ and opacity? Is this due to changes in $\nabla_{\rm rad}$ or $\nabla_{\rm ad}$? Why do these changes occur? At what temperature is the opacity the greatest? Where is this in the star (find the M and R coordinates)?

2.4 Kippenhahn Diagrams

The final *WTTS* tab we are going to look at is 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. In *WTTS* this idea is extended to allow *any* variables on the x and y axes, and *any* variable for the colour (mapped surface) plot.

First we will make a traditional Kippenhahn, then try making some fun colour plots.

1. Select the *Kippenhahn* tab.
2. You should see the usual *Star 1/2* selector, just leave this at *Star 1*.
3. 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).
4. 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 it is assumed you have been through that section.
5. The ranges can also be set in the boxes (autoscaling is again marked with an asterisk *).
6. For the x and y axes you can set the *resolution*. A setting of 100% means that every point in a model is plotted, a settings of 10% means that every tenth point is plotted. A lower resolution will plot more quickly, so is useful for a quick sketch. Setting *WTTS* to high resolution may take a long time to plot, especially for long model sequences, because the amount of data that must be accessed is very large. This effect will be even worse if you are using a slow hard disk or your data is being transferred across a network (you have been warned!).
7. The *Palette* section allows you to change the colours.

8. 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.

9. 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.

2.4.1 Traditional Kippenhahn Plots

1. 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* is actually $\max\left[\nabla_{\rm rad} - \nabla_{\rm ad}, 10^{-30}\right]$, so is positive when there is convection, and tiny when there is not. Taking the log means we show only the convective regions. Set the resolutions at 10% and 10%. Hit replot.

2. You will see mostly black, which corresponds to -30 in the colour key. This is because $\nabla_{\rm rad} - \nabla_{\rm ad}$ is 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 $\nabla_{\rm rad} - \nabla_{\rm ad}$ to something very small (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*.

3. Now you see a coloured band across the top, but it is very jerky. Set both the resolutions to 50% (and hit *replot*) and there will be fewer jerks. Try 100% – this is the best we can do with the current data. If we decide that we need finer spacing, we would need to re-run the evolution with smaller timesteps so that we have more data to plot.

4. Remove the range setting, set the resolution to 100% and press *replot*.
   What is the depth of the convective envelope in the Sun? Does it vary over most of its lifetime?

2.4.2 Enhanced Kippenhahn Plots

1. We can compare to the work of the previous sections. Set the y axis to plot the radius R instead of M. Hit *replot*.

2. Now you can see that the *depth* of the envelope is nearer the 30% often quoted – it depends on whether we use R or M as a coordinate.

3. You can of course plot anything in these diagrams. Try plotting model number on the x axis, M on the y axis and T on the z axis. You can clearly see the temperature increase in the centre towards the end of the model run.

4. Plot the same thing with R as the y coordinate.

5. Replot with M as the y coordinate, and the oxygen abundance as the z coordinate. Now try H and He as the z coordinate.

6. Experiment with the palette. Some colours will be better than others, it depends on what you want to see.

Q8 Use the *Kippenhahn* tab to answer these questions.

a. Take a picture of the graph with H as the z axis, age on the x axis, and mass on the y axis. Explain what you see.

b. Plot *Age*, *M* and *E_nuc* (the last in *Log*, the rest *Linear*). This shows the nuclear burning regions. What happens to the burning region when the core runs out of hydrogen? What happens to the magnitude of the burning? Hint: try setting the y range maximum to (say) 0.3 to focus on the central region.

c. Change *Age* to *Model Number*. Replot. You can see that it is much easier to see the details of the transition from core to shell burning when plotting against *Model Number*. This is often the case and is a trick worth remembering. Why does this work? Why is the model number not simply linearly proportional to time?

d. Change back to *Age* for the x axis and try *L* on the z axis (*linear*). Can you explain what you see? Compare the maximum luminosity with the values in the HRD. Is there an error somewhere? What do you think has happened?

3 The ZAMS

Now that you know how to use *WTTS* we are going to move from a $1\,\mathrm{M}_\odot$ model to a complete *Zero Age Main Sequence* model set. This is a set of models which are all at the beginning of their evolution (*Zero Age*) but vary in mass. In this case we are going to make models between 0.5 and $20\,\mathrm{M}_\odot$.

3.1 Constructing the ZAMS models

1. Start *WTTS*
2. Click *Reset from defaults*
3. In the *Options* tab, find the *Mass Loss and Gain* subtab. Set *INIT_DAT.CMI* to 1e-9 (this means 10^{-9} in floating point notation).
   CMI is an artificial mass gain rate in $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.
4. In the *Mass Loss and Gain* tab set *INIT_DAT.CMR* and *INIT_DAT.CMJ* to 0. This turns off mass loss.
   Why do we do this?
5. In the *Operation Mode* tab set *INIT_RUN.KPT* to 1095.
6. Find the *Artificial Physics* tab and set *INIT_DAT.KTH* to zero.
   KTH multiplies the thermal energy term in the stellar structure equations. Why should we set this to zero?
7. Find the *Nuclear Network* subtab (you will have to scroll to the right using the arrow). Set *INIT_DAT.KCN* to 1.
8. In the *Options* tab, select the button *From ZAMS Library* so we start with a ZAMS model.
9. Select the nearest initial mass to $0.5\,\mathrm{M}_\odot$ (also make sure *From ZAMS Library* is set, and that $Z = 0.02$).
10. Go to the *Evolve* tab. Hit *Evolve*.
11. Click on *Follow Log* to see what's going on (you may need to click *Update Log Window* to get it going). You can either follow the log (if you can work out what it means) or just look at the status bar. Because we are evolving *Zero Age* models the age given by $t = \ldots$ is spurious and does not conform to any real time. You should instead look at $M = \ldots$ which gives the current mass, which should be going up.

3.2 HRD of the ZAMS

1. Go to the *HRD* tab and construct an HR diagram of the zero-age main sequence which is labelled by the mass. Play with the line width and the label spacing to make the HRD look as good as possible.

2. Questions: What colour are low mass main sequence stars? What colour are high mass main sequence stars?

Q9 Use your new HRD to answer these qustions.

a. Print your HRD and label the spectral types O, B, A, F, G, K and M.
b. What was the temperature and spectral type of the Sun when it was born?

3.3 Mass-Luminosity relation

1. Go to the *Structure* tab.
2. Plot *Mass* on the x-axis, *log Luminosity* on the y-axis.

Q10 Use your new HRD to answer these qustions.

a. Estimate an expression for the luminosity L as a function of mass M in the form $L \propto M^n$.
b. Instead of luminosity, plot radius. Estimate a function $R(M)$.

3.4 Convection

1. Go to the *Kippenhahn* tab.
2. For the x-axis choose *Mass* and make sure it is logged.
3. For the y-axis choose *M/Mass* (linear).
4. For the z-axis choose *Convection* and make sure it is logged.
5. Hit *Replot*.

Q11 Use your new HRD to answer these qustions.

a. What is the minimum mass for a star to have a convective core on the ZAMS?

b. What is the maximum mass for a star to have a surface convection region?

c. Try plotting $\log T$ instead of convection (hint: try setting the z-Range minimum to 6 to get better contrast). Why are higher mass stars hotter?

d. Plot *rho* (the density) instead of T (remember to reset the z-Range! Try setting the minimum to -2 to get better contrast). What do you see now?

e. Plot *E_nuc* (you should set the ranges to suitable values because some regions of the star will have *E_nuc* set to a very small number, effectively zero). Comment on the central concentration of the energy production as a function of mass.

f. You can split *E_nuc* into the contributions from the *pp* and CNO burning cycles. Instead of plotting *E_nuc*, try plotting

   a) RPP (the *pp* chain burning rate)
   b) RPC (the $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^+,\nu)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$ burning rate)
   c) RPNG (the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^+,\nu)^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$ rate)
   d) RPN (the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^+,\nu)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$ rate)
   e) and RPO (the $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(\beta^+,\nu)^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ burning rate).

   and describe (qualitatively) what is the relative contribution to the nuclear burning rate from each reaction as a function of mass?