

Simulating Stars — White-Dwarf Luminosity Functions

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1 Introduction

White dwarfs are the final stage in the evolution of stars less than about eight solar masses. Basically, all nuclear energy generation has ceased, so the stars shrink and cool.

We have created several models of very young white dwarfs from the evolution of stars of one, two, four and eight solar masses for you to explore the subsequent evolution.

We will look at how white dwarfs move through the Hertzsprung-Russell diagram and colour-magnitude diagrams as they age and also examine the luminosity function of white dwarfs, i.e. how many white dwarfs are there of a given brightness.

2 The work folder

In the `$MESA_DIR/star` there is a folder called `work`. It is provided as a start folder for your projects. For this lab, we took the `work` folder, renamed it to `wd_lab` and made a few changes to the inlists.

For the main inlist, called `inlist_project`, we created an inlist very similar to the inlist of the `test_suite` directory `wd_cool`. It loads a model that we already ran all the way past the end of the AGB and evolves it as it becomes a white dwarf and cools down. The reason why we didn't use the `test_suite wd_cool` in the first place, is because the `test_suite` is structured in a way that only the late stages of the white dwarf cooling are saved in the `history.data`, while we are interested in the entire sequence. Take a look at the inlist to see what type of commands are there.

Also, we used the same `inlist_pgstar` as the one we created on the first day, with the difference that instead of a Kipp diagram, now there is a diagram of the total luminosity and the neutrino luminosity vs the age of the star. Feel free to change the `inlist_pgstar` to show other interesting properties of the white dwarf as it evolves.

But before starting the run, we need to make some changes.

Task:

In `inlist_project`, the value called `mesh_delta_coeff` is set equal to 2. This parameter determines how fine the mesh is: a larger value increases the max allowed deltas and decreases the number of grid points and a smaller does the opposite. e.g., you will roughly double the number of grid points if you cut `mesh_delta_coeff` in half. We need a high value of `mesh_delta_coeff` in the first few models to help the run relax, but we want a finer mesh for later stages.

Also, the atmosphere boundary condition are set to `which_atm_option = 'grey_and_cap'`. These are ok for high temperatures, but for effective temperatures lower than 40,000 K, the boundary conditions called `'WD_tau_25_tables'` are much better for a WD.

We want to use `run_star_extras.f` to make those changes. If you open the file `src/run_star_extras.f`, you'll see that it doesn't contain the usual routines, but it includes the file `standard_run_star_extras.inc`. This file can be found in the folder `$MESA_DIR/include`.

1. Copy the content of `standard_run_star_extras.inc` into the `run_star_extras.f` file in place of the line `include 'standard_run_star_extras.inc'`. You can see that these are just the standard `run_star_extras` routines. After copying the content into your `run_star_extras.f`, it is safe to try and make your folder to check if you copied everything all right.

2. Use `run_star_extras.f` to change the `mesh_delta_coeff` to 0.7 after the 15th model.
3. Use `run_star_extras.f` to change the atmosphere boundary conditions to 'WD_tau_25_tables' when the effective temperature falls lower than 40,000 K.

Solution:

```
! returns either keep_going or terminate.
! note: cannot request retry or backup; extras_check_model can do that.
integer function extras_finish_step(id, id_extra)
  integer, intent(in) :: id, id_extra
  integer :: ierr
  type (star_info), pointer :: s
  ierr = 0
  call star_ptr(id, s, ierr)
  if (ierr /= 0) return
  extras_finish_step = keep_going
  call store_extra_info(s)

  ! to save a profile,
  ! s% need_to_save_profiles_now = .true.
  ! to update the star log,
  ! s% need_to_update_history_now = .true.

  ! see extras_check_model for information about custom termination codes
  ! by default, indicate where (in the code) MESA terminated
  if (s% model_number == 15) then
    s% mesh_delta_coeff = 0.7
  endif

  if (s% Teff < 40000) then
    s% which_atm_option = 'WD_tau_25_tables'
  endif

  if (extras_finish_step == terminate) s% termination_code = t_extras_finish_step
end function extras_finish_step
```

3 The Evolution

As the `52SMWD.mod` runs, take a look at the Jupyter notebook called White-Dwarf-Lab. A few example plots are shown for a `history.data` file that comes from the evolution of a more massive WD ($M = 1.17 M_{\odot}$).

Task:

1. Let's first look at the track of luminosity against effective temperature. What is happening to the star?
2. Let's look at luminosity against core temperature. What is happening here? What are the different regimes?
3. Let's look at luminosity against time. What are the different regimes here?
4. When the run for `52SMWD.mod` stops, try loading its `history.data` file in the notebook and add its curves to the plots. This model is for a white dwarf that results from a one-solar-mass star. This is typical for the white dwarfs in globular clusters. What are the differences?
5. If you have time, try running the evolution for a more massive white dwarf and add their curves to the preceding diagrams.

Hint:

You may find that some of the models fail to run. You can try increasing the number of retries and backups or changing the `varcontrol` parameter.

Bonus Task:

You can use the include program `makefakehistory.py` to recalculate the thermal evolution assuming that specific heat capacity of the star is constant (it remains liquid) or that the cooling is due to emission of radiation from the surface. Compare the results of these simulations to the original ones.

4 Observations

4.1 The outer field

We have included a file with the observed fluxes of about 2,000 old white dwarfs in the globular cluster 47 Tucanae. The white dwarfs that are being born in this cluster come from stars whose masses are just a bit less than the mass of the Sun. Because the white dwarfs are relatively young compared to the age of the cluster, we can assume that they are being born at a constant rate, so their cumulative luminosity function is an estimate of their cooling evolution.

The file with the observed white dwarfs is called `47tuc_fromIR.dat` and presents the observed magnitudes in the Hubble filters `F814W` (second column) and `F606W` (third column), and the difference between the two (first column).

Task: Old White Dwarfs

1. Use the `paintisochrone.py` program to add absolute magnitudes to your history files. We have provided an atmosphere file for this called `colmag.Bergeron.all.Vega.txt`. The code needs three arguments, the name of the history file, the name of the atmosphere file, and the name of the output file. In the Jupyter notebook you can see the example we made for the `history_example.data` file that we provided.
2. Plot the colour $F814W$ against $F606W - F814W$ from your models
3. Plot $F814W$ against time.

Now that we have the magnitudes in 814 and 606, we can finally compare our models with observations.

Task:

1. Load the file `47tuc_fromIR.dat`.
2. Make a CMD plotting the colour $F814W$ against $F606W - F814W$ from the data. This is the WD cooling sequence of 47 Tucanae.
3. Add both theoretical curves on the plot: the one called `paintedhistory_ex.data` and the one you made. And others if you made more than one.
4. You can see that both of them fall far from the data. That's because the models are still in absolute magnitudes, while the data is in observed magnitudes. In order to compare them, we need to add the distant modulus (13.45) and reddening (0.065) to the models, for example:

```
plt.plot(pdata['F606W']-pdata['F814W']+0.065,pdata['F814W']+13.45,c='r')
```

5. Now we can compare them. Which evolution does the data agree with the best?

If we assume that the white dwarfs in the cluster are born at a constant rate, we can use their cumulative luminosity function as a proxy for their cooling evolution. In the file `47tuc_fromIR.dat` there is a column called 'cumweight', that indicates, for each star, how many stars we expect in the field at that magnitude or brighter. This cumulative distribution is calculated by counting how many stars are in the image and correcting the number for the ones that the telescope might have missed (the completeness is given as a percentage in the column 'comp'). In this field, which is in the outskirts of the cluster, we estimated the birth rate to be about 1 WD every 6×10^6 years.

Task:

1. Plot the magnitude in $F814W$ against the cumulative distribution divided by the birth rate (you can just multiply 'cumweight' by 6×10^6 years). You will get the cooling curve of the white dwarfs in the cluster. Make the x-axis logarithmic.
2. On top of it, plot the magnitude in $F814W$ against the log of the star age for your theoretical models. And don't forget to add the distance modulus!

3. Since the zero age of the WD we chose is arbitrary, you might have to add or subtract some small constant to the age of your models to make them fit better the data.
4. Which evolution does the data agree with the best?

Bonus Task:

If one of your white dwarf evolutions lasted long enough, you will see the effects of the onset of convection in the cooling track. Compare this model with observations. Plot the profile files that correspond to when the bump in the cooling curve occurs to verify that both convection and freezing are occurring. Perhaps add entropy information to the profile and re-run.

Hint:

The key parameter to plot is the specific entropy but it doesn't get output in the profile file by default. You could add it and restart your run using the `re` command with a photo file or you could plot $\log P$ against $\log \rho$.

4.2 The inner field

In the file `47tuc_fromUV.dat` you can find the observed flux from about 3000 white dwarfs. These white dwarfs live in the center of the cluster, where the density of stars is extremely high. For this reason, it is hard to detect white dwarfs in the visible or in the infrared, as the light is dominated by the very bright red giants. However, young white dwarfs are the brightest objects in the UV, because they are very hot. That's why we observed them in the filters *F225W* and *F336W* with Hubble. You can see the UV image here: http://coolpulsars.org/images/47TucCore_Image/. The white dwarfs are the blue dots.

This set of young white dwarfs in the UV is what we are going to use in the next lab, so let's take a look at it.

Task: Young White Dwarfs

1. Make a CMD with the magnitude *F225W* against *F225W* – *F336W* from the data and from your models. The distance modulus is of course the same, but do you need to add reddening in these filters? How much?
2. Make a cumulative distribution plot for *F225W* as we did before for *F814W*. This time though, since we are in the center of the clusters and the density of stars is higher, we expect a higher birth rate. Can you figure it out from comparing the models with the data?

We will study the young white dwarfs in more detail in the next lab where you will program MESA to vary the neutrino rates within the white dwarfs and see what happens.