MESA Summer School 2015: X-ray Burst Lab

Lecturer: Andrew Cumming, TA: Rob Farmer

Objectives

In this lab, we will focus on bursts where the helium ignites in a hydrogen rich environment, and explore the effect of changing the nuclear network on the burst recurrence time and lightcurve. This will involve constructing nets of different sizes and using the adaptive net feature of MESA.

Part 1: Comparison to GS 1826-24

- As we discussed in the lecture, the best source to compare to is the very regular X-ray burster GS 1826-24. We have included a flag to add the average observed burst lightcurve from GS 1826-24 to the burst pgstar window. Turn this on using the control `show_gs1826=.true.` in the `inlist_for_my_pgstar_plots` file.
- To help to see which nuclei are included in the net and how the nuclear burning is proceeding, we have included a new pgstar window to show the nuclear chart. Turn this on using the control `net_win_flag=.true.` Next time you run MESA, the net window will appear showing the nuclear chart. Each nucleus in the network is shown as a square. The color of the square indicates the mass fraction of that nucleus averaged over the model.
- Run a model with $L_b = 1.6 \times 10^{34}$ erg s^{-1} and $\dot{M} = 3 \times 10^{-9}\ M_\odot$ yr^{-1} which will give a mixed H/He burst, matching the burning regime that we think GS 1826-24 is in.
- **Question:** How does the model burst lightcurve compare with the data? You can use the control `burst_scale_lum` to either normalize the peak luminosity of the bursts to match the GS 1826-24 burst, or to show everything on an absolute luminosity scale. Try both and see how the burst matches up in both shape and peak luminosity.

Part 2: A Bigger Net

Let's try using a different network to more accurately include rp-process hydrogen burning in the model. In this part, everyone will run the same model and we will compare results, especially the run time on different laptops.

- Copy the `rp.net` network file from MESA to your work directory. You'll find it in `mesa/data/net_data/nets/` along with many other choices of nets that can be used with MESA. If you look inside the file, you'll see that it uses the command `add_isos_and_reactions` to make a network of 304 different nuclei that are relevant isotopes for the rp-process up to $A \approx 100$. Unfortunately, MESA runs slowly with such a large network. To reduce the size of the net and keep the run time short, we'll make a smaller version of this net. To do this, open the file and comment out (by adding `!` to the start of the line, fortran style) all isotopes heavier than Si. This will remove them from the net. Also, add `fe56`, which is the composition of the deep layers.

- Using the `change_initial_net` and `new_net_name` controls, try running MESA with your truncated rp network. At the start of the run, MESA should report that it is using 54 isotopes in the net.

- You will find that MESA is running rather slowly compared to our earlier runs with the `cno_extras_plus_fe56` net. There are other controls that can be adjusted to reduce the run time further. We've done this for you in the file `inlist_ns_extras`. Add a `read_extra_controls_inlist2` command in the `&controls` section of the main `inlist` to include the additional inlist. When you run MESA again you should see a noticeable speed up.

- Run the model until it has evolved through three flashes, and report the following quantities in the google doc:

  - the recurrence time
  - the time it took to run the model, and the amount of memory being used (to check the memory usage, run `top` and look for the `star` process)
  - the peak luminosity
  - with the burst peak luminosities normalized in the burst window, measure the time after the peak of the burst where the model lightcurve starts to deviate significantly from the GS1826 data (this is a way to quantify how well the lightcurve matches the data)
  - the mass fraction of hydrogen in the ashes layer – i.e. how much hydrogen is present in the layer of heavy elements left over from previous bursts? You may want to change the axis limits on the abundance plot to help see this more clearly (e.g. zoom in on column depths between 8.0 and 8.5).

  You should measure these quantities as best you can from the pgstar windows.

Part 3: Smaller and Larger Nets

We see from the previous exercise that truncating the net at Si is not giving a good fit to the GS 1826 data. What network do we need to fit the GS 1826 data? Next, explore the effect of changing the net and see if you can optimize it to get better agreement.

- Work together with the other students on your table to run different networks and see how close a match to GS 1826 you can get. We found that nets up to 80 (peak element Ar) could run in about ten minutes, but it will depend on the speed and number of cores of your laptop. You may be able to do better. Limit the run to either three bursts or ten minutes of run time.

  Hint: The simplest way to change the net is by changing the last element from Si to some other element with a larger or smaller Z. But you can also be more creative: can you get to larger Z and still have a small enough network to run in ten minutes by removing some of the lighter elements that are not essential? Each element has a range of isotopes: can you reduce the range of isotopes and still get a good answer?

- For every net you try, report the same quantities as in Part 2 in the google doc, but this time also indicate the total number of isotopes and the largest Z in your net, and also add any comments on the run – e.g. were there any problems? did it run particularly slowly? do the bursts look unusual?

Part 4: Adaptive Net

A recent addition to MESA is the capability to have an adaptive net. The net automatically changes size as the calculation progresses, adding or removing isotopes as needed. Let's try it!

- Turn on the adaptive net. We need to set appropriate limits on Z and N so it doesn't get too large and we can run in a reasonable time. Add the following settings to the inlist:

```
enable_adaptive_network = .true.
min_x_for_keep = 1d-4
min_x_for_n = 1d-3
min_x_for_add = 1d-3
max_Z_for_add = 16
max_N_for_add = 16
max_A_for_add = 32
```

(You'll also have to comment out `change_initial_net`).

As the model runs, you will see the size of the network changing over time in the pgstar net window. Another way to look at what is happening with the net is to look in the `nets` folder that you should find in your local directory. It contains the nets used throughout the calculation. The numbers in the file name are the model number and the number of species in the net.

- You can also monitor the number of species in the network by adding `species` to the history columns. Replace the curve showing the number of zones in your pgstar window with the number of species in the network instead.
- Run the model. You should be able to get through a burst within 10 minutes. As the burst runs, answer the following questions:
  - Do you see the network changing in size in the net window?
  - Look at the history panel. How does the number of species in the network change with time, and how does it compare to the change of luminosity with time? Is it what you expect?
  - Looking at the burst window, you should see that the burst lightcurve has two peaks! Watch the net window carefully as the burst progresses – can you see what is happening to give the second peak? Can you make a simple adjustment to the controls for the adaptive net to remove the second peak?
- Now let's try the largest net so far. Change the settings to allow the net to expand up to ^{56}Fe. Run it and see how far you can get in ten minutes (you might want to work with the other students on your table and run this on the fastest laptop). As the run progresses, watch the net window carefully. Can you see particular nuclei that develop large abundances as the composition moves to larger and larger Z? What are these important nuclei? Looking at the burst lightcurve, how does the peak luminosity compare to GS 1826-24 now?

Questions for discussion:

- Given the sensitivity to the choice of network that we've seen here, it should be clear that you have to be careful to choose the right network. How do you choose which net to use, and how can you be sure it is the right one for the problem you are interested in?

- What else would you do to make sure you are getting the right answer before you used the lightcurves from MESA to compare to data or to write a paper?
- We've seen that these models are pushing MESA to its limits, with hundreds of nuclei required to follow all the nucleosynthesis during the X-ray burst and calculations that take several hours or more per burst. What improvements, changes, or additions could we make to the MESA code to improve performance?