MESA tutorial: Session 4

Binary stars and their interactions

Hand in your answers to all the numbered questions (i.e. 1 a, b, c etc.), they will make up your grade for the MESA practicum part of the course. refer to Chapter 15 of the lecture notes.

1 X-ray binaries and gravitational waves progenitors?

For this exercise, we will model the well-known X-ray binary SS433, (e.g., van den Heuvel et al. 2017). This binary consists of a blue supergiant ($M \approx 12.3 \pm 3.3$ M$_\odot$) and a stellar mass black hole ($M \approx 4.3 \pm 0.8$ M$_\odot$). The orbital period of the X-ray binary is approximately 13 days, and the blue supergiant appears to be losing mass to the black hole, creating the X-ray luminosity in the system.

We will model the evolution of this binary in the `binary` module in `MESA`, (different from the `star/work` directory you have used so far) treating the black hole as a point mass. This is a good approximation if you are interested in the evolution of the donor star and the binary system when the companion is a compact object.

- Download the work folder from Brightspace (`session4.tar`) and inspect the inlists Can you identify which inlist details the settings for the binary system and for the donor star?.
- Get familiar with some of the controls that are available. If necessary, go to the website and get more information under the tab `binary_controls defaults`[1], or check the files: `$MESA_DIR/binary/defaults/binary_controls.defaults` `(...)binary_history_columns.list`, and `(...)binary_job.defaults`.
- Modify the physical parameters of the system to approximately match the X-ray binary SS433. While you can choose values for the mass of the donor star and of the black hole within the observed error bars, `MESA` has a tendency to get stuck for a lot of mass configurations. Configurations that do run are for example $M_1 = 12$ M$_\odot$ and $M_2 = 3.5$ M$_\odot$, or $M_1 = 9$ M$_\odot$ and $M_2 = 4$ M$_\odot$. Set the initial period to 15 days.

Note that a black hole cannot accrete material at an arbitrarily high rate. The accretion rate is limited by the Eddington rate (related to the Eddington Luminosity), above which radiation pressure from the accreting material pushes incoming matter away. The Eddington accretion rate is given by

$$\dot{M}_{\rm Edd} = \frac{4\pi c R_{\rm acc}}{\kappa} \approx 3.3 \times 10^{-4} M_\odot/{\rm yr} \left(\frac{R_{\rm acc}}{R_\odot}\right),$$

where $R_{\rm acc}$ is the radius at which material is accreted. Fortunately, you do not have to implement this formula in `MESA` yourself.

- Look for a control that limits the accretion rate to the Eddington accretion rate[2]. Add this to `&binary_controls` in `inlist_project`.

[1] `https://docs.mesastar.org/en/release-r22.05.1/reference/binary_controls.html`

[2] `https://docs.mesastar.org/en/release-r22.05.1/reference/binary_controls.html#mass-transfer-controls`

- Now compile (`./mk`) and run (`./rn`) the code.

(a) Plot and inspect the HR diagram of the donor. Can you identify the start and end of the mass transfer phase? (Compare with the single star evolution track from the previous MESA session). What type of mass transfer is occurring (Case A, B, or C)?

(b) Plot the donor's mass transfer rate versus the stellar age. Zoom in on the mass transfer phase.[3] Is the donor mass transfer rate higher or lower than the Eddington rate? (Assume R_{acc} is equal to the Schwarzschild radius of the black hole). Is the black hole is accreting all the material lost by the donor star?

At the end of your simulation you formed a helium star in an orbit around a black hole. The fate of such a helium star is not well known, but let's speculate:

(c) If the helium star directly collapses to a black hole, it will form a binary black hole system. What would be the final black hole masses and their orbital separation?

(d) Eventually these two black holes will merge due to the loss of angular momentum in the form of gravitational waves. The time it takes for a double black hole system to merge is given by:

$$\tau_{\mathrm{merge}} = 1.503 \times 10^8 \,\mathrm{yr} \times \frac{1}{q(1+q)} \left(\frac{a}{R_\odot}\right)^4 \left(\frac{M_1}{M_\odot}\right)^{-3},$$

where M_1 is the mass of one of the black holes and the mass ratio is defined as $q = M_2/M_1$.

How long will it take for your black hole binary system to spiral in? Would LIGO and VIRGO be able to detect this?

2 Simultaneous evolution of two massive stars in a binary

Instead of treating the secondary star as a point mass, we can evolve both stars at the same time in `MESA`. In this exercise, we will simulate the evolution of two massive stars in a close binary system, starting from the ZAMS.

- Copy the work folder from the previous exercise and adapt `inlist_project` to evolve a 15 $\mathrm{M}_\odot$ primary star with a 13 $\mathrm{M}_\odot$ secondary star in a 15 day orbit.

  Make sure to tell `MESA` to evolve both stars. Look for the setting `evolve_both_stars` in the binary controls and switch it on.

- Furthermore, we will assume that the accreting star accretes only half of the mass transferred by Roche-lobe overflow. Check your inlist and make sure that the mass transfer efficiency is equal to 0.5[4]. Finally, turn the Eddington accretion limit off again, as this inherently assumes the companion star to be a black hole.

- `./clean`, make `./mk`, and run `./rn`

- Look at the plots from `PGSTAR`. Specifically have a look at the diagram that shows the central hydrogen abundance versus time. Which star is running out of hydrogen first? Is this what you expect? Does the surface hydrogen abundance change? Is this what you expect?

[3] Make sure to use appropriate x and y lims when you plot the eddington accretion rate and donor mass transfer rate.

[4] `https://docs.mesastar.org/en/release-r22.05.1/reference/binary_controls.html#mass-transfer-controls`

(a) Load the `binary_history.data` and plot the masses of the donor and accretor star over time. How do the masses of the stars change? How much mass does the donor star lose, and how much of this mass does the other star accrete? Is this what you expected?

(b) Look at the Kippenhahn diagram (or plot your own!). What happens to the convective core of the secondary star as it accretes more mass? How does this change the abundances in the core? Explain why it is appropriate to say that mass accretion 'rejuvenates' a star. Could such a star appear as a 'blue straggler'?