Massive Stars Near and Far
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How to make an 85 Solar Mass Black Hole

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Abstract. We present in-progress resolution test and parameter space studies for very massive stars using MESA, showcasing current MESA version convergence studies.

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1. Introduction

The Pair Instability (PI) mass gap is predicted from approximately 60 to 130 $M_\odot$ (Fowler & Hoyle (1964)), and defines a region where no black hole from direct core collapse should be found. However, with the gravitational wave detection, GW190521, two black holes of 66 (+17, -18) and 85(+21, -14) solar masses merged to form a 146 solar mass black hole (Abbott *et al.* (2020)). This prompted the theory that the two component black holes were themselves the products of mergers from black holes below the PI mass gap. However, Vink *et al.* (2021) showed that a black hole on the order of 85 solar masses could be formed from single star evolution, so long as the star in question maintained a low core mass. Extending on that research, this work aims to investigate stellar evolution inside of the PI mass gap and provide a likelihood of black hole formation, across a range of initial conditions. To do this, I use the Modules for Experiments in Stellar Astrophysics (MESA) (Paxton *et al.* (2011)) code to evolve stars throughout their full evolution until core collapse. The aim of this work is to critically and systematically assess black hole formation in the PI mass gap, provide insight into stellar evolution at high stellar mass regimes, but primarily it is to establish the total likelihood of black hole production in this regime and attempt to provide a clearer answer on the origin of large stellar mass black holes, such as those seen in GW190521. By exploring a range of parameters which is outlined in Section 2, it will become clear which regions of the parameter space are more prone towards making black holes, and the limits of these parameters in this context.

2. Methods

Using the MESA code we have a large grid of models spanning the Pair Instability mass gap across full evolution, with multiple varying parameters. Firstly, the resolution of the models should be to converged to ensure that future results are consistent. Secondly, the grid is set up and run to provide insight into the final fates of single stars who are in the PI mass gap.

The parameters varied are:

- Initial mass, M_i, between 60 and 150 solar masses,
- Initial metallicity, Z_i, between 1×10^{-5} and 1×10^{-1},

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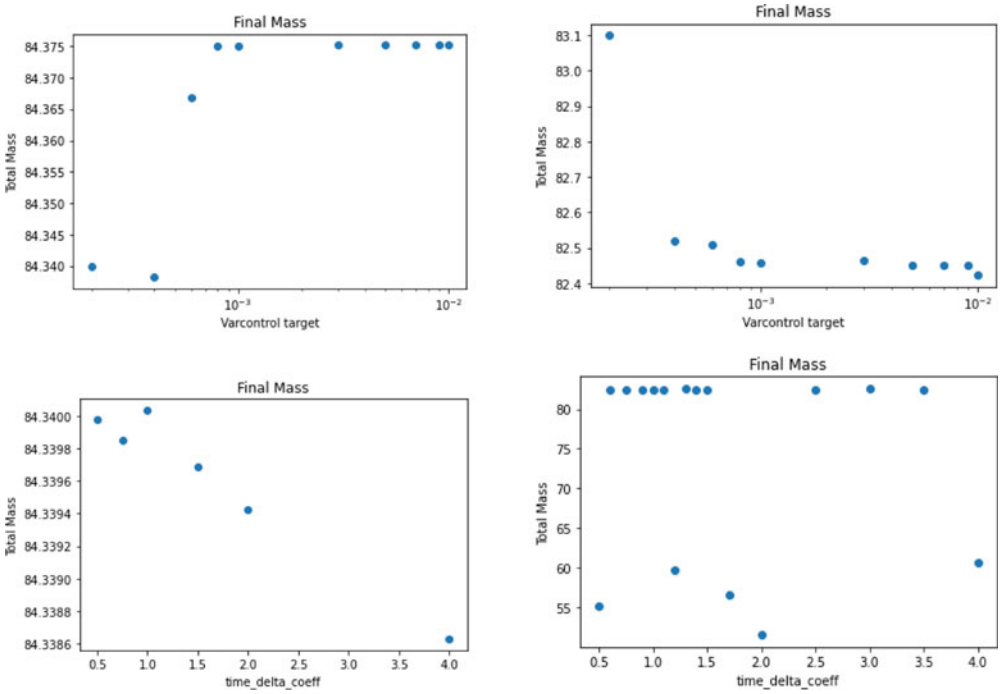

Figure 1. Final mass of stellar evolution models. The left panels are for main sequence evolution, while the right panels represent stars which have completed core Helium burning. The varying resolution parameter in the top two panels is *mesh_delta_coefficient*, while the bottom two are for *time_delta_coeff*.

- Initial rotation, $\Omega/\Omega_{critical}$, from 0, so non-rotating, to 0.6,
- Overshooting, f_0, from 0.1 to 0.5,
- and the Spruit-Taylor Dynamo which is either *on* or *off* at 1 or 0.

In order to be sure that the results of the aforementioned grid are converged, studies on the resolution parameters in MESA need to be conducted. The MESA version used, r15140, has two main resolution parameters - *mesh_delta_coefficient* and *time_delta_coefficient*. However, it should be noted that for versions before this, the parameter *varcontrol_target* was used instead. This variable was phased out in r15140 in favour of *time_delta_coefficient* and a limit is now placed on *varcontrol_target*, though this can be overridden.

3. Conclusions

Due to the size of the stars in this grid, the resolution parameters for MESA have shown to produce inconsistent results for small variations, with no clear convergence for the given spatial or temporal parameters. As shown in Figure 1, stars during Helium burning (right panels) did not provide a clear trend of the resolution parameters to final mass when varying *time_delta_coefficient* (bottom right panel), unlike the top right panel which shows a varying *varcontrol_target*. The mass discrepancy seen in the bottom right panel of Figure 1 is an unphysical numerical result at the boundary of the core and the shell wherein the model runs away and becomes hot and luminous, with a large convective region. If using a metallicity dependent wind, then this will lead to increased mass loss.

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