Stellar Mergers as Pair Instability Supernova Progenitors

Alejandro Vigna-Gómez[1,2]

[1]Birmingham Institute for Gravitational Wave Astronomy and School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, United Kingdom
[2]DARK, Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100, Copenhagen, Denmark

E-mail: `avigna@star.sr.bham.ac.uk`

Stephen Justham[2,3,4]

[3] School of Astronomy & Space Science, University of the Chinese Academy of Sciences, Beijing, China
[4] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

E-mail: `sjustham@ucas.ac.cn`

Philipp Podsiadlowski[2,5]

[5] Department of Astronomy, Oxford University, Oxford OX1 3RH, United Kingdom

E-mail: `podsi@astro.ox.ac.uk`

Abstract. In this report, we discuss the progress on the summer research project done in the "Kavli Summer Program in Astrophysics 2017". This project consists in modeling pair-instability supernovae from merger products. Single stars with a carbon-oxygen core less than ≈ 64 M$_\odot$ will not achieve conditions for efficient pair creation, but suitable merger products may do so. This has previously been mostly ignored, both in modelling potential individual pair-instability explosions and in understanding likely populations of pair-instability events. The two main potential routes to producing pair-instability supernovae from massive binary mergers are also closely related to popular field binary formation channels to black hole mergers; understanding this explosive merger population should help to constrain those kindred routes. We model the products formed by merging $82 + 82$ M$_\odot$ and $110 + 110$ M$_\odot$ pairs of early post-main-sequence stars at solar metallicity. After the merger, they both reach the pair-instability region. This channel may therefore produce pair-instability supernovae even at relatively high metallicity, unlike single-star expectations, and might perhaps even dominate the rate in the local universe. We model the merger product of two $82{+}82$ M$_\odot$ and $110 + 110$ M$_\odot$ stars. After the merger, they both reach the pair-instability region.

Keywords: Pair-instability supernovae, stellar mergers

1. Introduction

Pair-production instability as an explosion mechanism for a single star was initially proposed by Barkat et al. (1967), Rakavy et al. (1967) and Fraley (1968). Single stars with $\approx 64 - 133$ $M_{\odot}$ (see Heger & Woosley (2002)) cores end up their life exploding as a pair-instability supernova (PISN). Stars with a core of less than ≈ 64 $M_{\odot}$, which are not PISN candidates, may reach the unstable pair-creation region if they merge with another star. While single stars require low metallicity environments to build up a core (see Heger et al. (2003)), appropriate merger products may be able to become PISN progenitors at higher metallicities. Suitable stellar mergers may happen during different evolutionary stages, e.g.:

(i) Massive overcontact binaries are close and well mixed stars which evolve through ZAMS with one or several mass exchanging episodes (case A). They end up having mass ratios close to one. After their main sequence evolution, some of them will merge. These merging systems could be massive enough to be progenitors of a black hole or a PISN, depending on the merger mass. This form of evolution is not well understood, and is of particular interest for producing LIGO merger sources with similar masses to GW150914 and GW170814; hence independent constraints from understanding a closely-related outcome would be valuable. For more details see Marchant et al. (2016).

(ii) Post main sequence systems with similar evolutionary timescales may allow for cores to merge (case B). In the case the core product of the merger is above ≈ 64 $M_{\odot}$ (see. Heger et al. (2003)), a PISN can occur. This allows for systems with a maximum core mass of less than ≈ 64 $M_{\odot}$, which wouldn't get into the pair unstable region on their own, to become PISN as merger products. Further comments in Justham et al. (2014).

(iii) In rare circumstances, a suitable merger may happen when one of the stars has already completed core helium burning (case C). Whilst this requires some fine-tuning, if the rate is not negligible then these progenitor structures and resulting explosions could be especially interesting.

The aim of this project is to analyse if merger products can become PISN, particularly as case B mergers. The report is structured in the following way. In section 2 we discuss the modeling of the mergers. In section 3 we present the results and comment on the most relevant parts of it. Finally, in section 4 we discuss the future work to finish this project.

2. Methods

To study the progenitor candidates of PISN we used the Modules for Experiments in Stellar Astrophysics stellar evolution code, as presented in Paxton et al. (2010), Paxton et al. (2013) and Paxton et al. (2015). Our models are based on single stellar evolution, merger, and merger products evolution. The setup is the following:

(i) Metallicity: we evolve high metallicity stars mimicking local environments.

(ii) Systems: we model different mergers, 82 $M_\odot$ and 110 $M_\odot$ binary systems, both with mass ratio $q = 1$.

(iii) Single stellar evolution: We evolve our initial model until central hydrogen abundance is depleted to less than 10^{-15} and a convective core has receded enough to have a clear core-envelope separation. At that point, we stop the evolution.

(iv) Merger: Our early case B mergers are simulated by relaxing the initial mass to double its value, while maintaining the element abundances fixed.

(v) Post-merger evolution: Once our stars have merged, we resume the evolution of the product as far as possible.

(vi) Pair creation regime and PISN diagnosis: we use the central temperature vs central density diagram, a proxy of the temperature and density of the core, to determine if the model enters the unstable pair creation region.

(vii) Post-PISN abundances: if the model enters the pair creation region, we keep evolving the model to see how the element abundances change, particularly heavy elements such as nickel.

3. Results and discussions

Here we present and discuss the results of our models.

82+82 $M_\odot$ **model**

The $82 + 82$ $M_\odot$ model was proposed as an attempt to look for the lower mass merger (with $q \approx 1$), at high metallicity (solar) which can still form a PISN. We start evolving an 82 $M_\odot$ star from ZAMS to hydrogen depletion (for more details see 2). At the moment of merger, the star has lost about 30 $M_\odot$ through winds; the merger product is about 100 $M_\odot$ (see Fig. 3 for details). The merger product has an oxygen core of ≈ 70 $M_\odot$, which enters the pair creation region, burning oxygen and realising energy, driving a shock. The system becomes unbound due to this released energy. For the 45 elements reaction network, the final element abundances before stopping the evolution is shown in 3. Higher elements reaction networks will generate heavier elements and more qualitative information about how the PISN will proceed.

110+110 $M_\odot$ **model**

The $110 + 110$ $M_\odot$ model is a more conservative one, in the sense that we expect it to become a PISN easily. It proceeds in a very similar way as the previous model, with a merger mass of ≈ 165 $M_\odot$ and an oxygen core of ≈ 110 $M_\odot$. This system also becomes pair unstable, with a more energetic explosion than the aforementioned system. It also becomes unbound and generates heavier elements. For details, see Fig. 3.

While we attempted mergers of different masses with more sophisticated methods, such as entropy sorting, numerical instabilities occurred. It is important to model different mass mergers, as they are dominant. An important feature differentiating between merger models would be the electromagnetic signature. Light curves from a PISN from a case B merger should differ from a case C merger, as the latter would have a thicker envelope. Circumstellar medium is crucial in the brightness of a supernova.

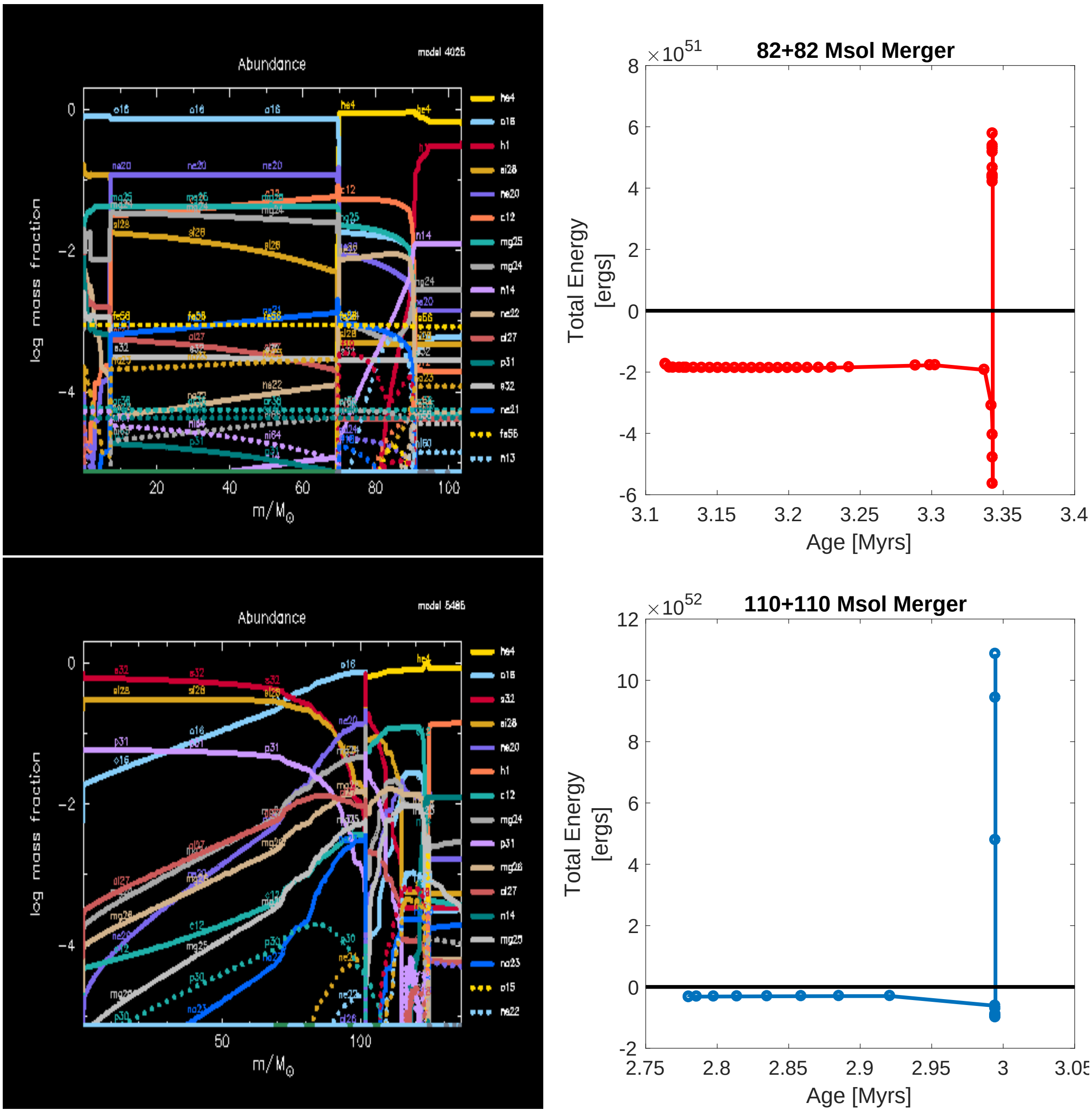

Figure 1. Preliminary visualisations of the results.
Top: 82+82 $M_\odot$ merger model. 45 element reaction network.
Bottom: 110+110 $M_\odot$ merger model. 45 element reaction network.
Left: Fractional element abundance as function of mass coordinate. This abundance corresponds to the last timestep before the model is terminated, where the shock has already been propagated. Default output settings from MESA.
Right: Total energy of the post-merger model as a function of the age of the star, where $age = 0$ Myrs is equivalent to ZAMS. Total energies where $E > 0$ (thick black horizontal line) suggest that the system is gravitationally unbound. At that point, the energy released during oxygen deflagration has overcome the binding energy of the star. We consider that this indicates these post-merger star each explode as a PISN, but have planned numerical experiments to further investigate the details of the outcome before publication.

4. Future work

There are models and validations to be finished in this ongoing project. We list the most relevant ones.

(i) Reproduce the 200 $M_\odot$ and 250 $M_\odot$ models from Kozyreva et al. (2016).
(ii) Compare to single models of masses $82 + 82$ $M_\odot$ and $110 + 110$ $M_\odot$ at ZAMS.
(iii) Model different mass mergers ($q \neq 1$).
(iv) Model MOB and case C mergers.
(v) Better treatment of the shock during the explosion.
(vi) Heavy element abundances in order to predict light curves.
(vii) Population and rate estimates.

5. Acknowledgements

We thank the Niels Bohr Institute for its hospitality while part of this work was completed, and acknowledge the Kavli Foundation and the DNRF for supporting the 2017 Kavli Summer Program.

References

Barkat, Z., Rakavy, G. & Sack, N. (1967), 'Dynamics of supernova explosion resulting from pair formation', *Physical Review Letters* **18**(10), 379.

Fraley, G. S. (1968), 'Supernovae explosions induced by pair-production instability', *Astrophysics and Space Science* **2**(1), 96–114.

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N. & Hartmann, D. H. (2003), 'How massive single stars end their life', *The Astrophysical Journal* **591**(1), 288.

Heger, A. & Woosley, S. E. (2002), 'The nucleosynthetic signature of population iii', *The Astrophysical Journal* **567**(1), 532.

Justham, S., Podsiadlowski, P. & Vink, J. S. (2014), 'Luminous blue variables and superluminous supernovae from binary mergers', *The Astrophysical Journal* **796**(2), 121.

Kozyreva, A., Gilmer, M., Hirschi, R., Fröhlich, C., Blinnikov, S., Wollaeger, R. T., Noebauer, U. M., van Rossum, D. R., Heger, A., Even, W. P. et al. (2016), 'Fast evolving pair-instability supernova models: evolution, explosion, light curves', *Monthly Notices of the Royal Astronomical Society* **464**(3), 2854–2865.

Marchant, P., Langer, N., Podsiadlowski, P., Tauris, T. M. & Moriya, T. J. (2016), 'A new route towards merging massive black holes', *Astronomy & Astrophysics* **588**, A50.

Paxton, B., Bildsten, L., Dotter, A., Herwig, F., Lesaffre, P. & Timmes, F. (2010), 'Modules for experiments in stellar astrophysics (mesa)', *The Astrophysical Journal Supplement Series* **192**(1), 3.

Paxton, B., Cantiello, M., Arras, P., Bildsten, L., Brown, E. F., Dotter, A., Mankovich, C., Montgomery, M., Stello, D., Timmes, F. et al. (2013), 'Modules for experiments in stellar astrophysics (mesa): planets, oscillations, rotation, and massive stars', *The Astrophysical Journal Supplement Series* **208**(1), 4.

Paxton, B., Marchant, P., Schwab, J., Bauer, E. B., Bildsten, L., Cantiello, M., Dessart, L., Farmer, R., Hu, H., Langer, N. et al. (2015), 'Modules for experiments in stellar astrophysics (mesa): binaries, pulsations, and explosions', *The Astrophysical Journal Supplement Series* **220**(1), 15.

Rakavy, G., Shaviv, G. & Zinamon, Z. (1967), 'Carbon and oxygen burning stars and pre-supernova models', *The Astrophysical Journal* **150**, 131.