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Massive Stellar Mergers as Precursors of Hydrogen-rich Pulsational Pair Instability Supernovae

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Abstract

Interactions between massive stars in binaries are thought to be responsible for much of the observed diversity of supernovae. As surveys probe rarer populations of events, we should expect to see supernovae arising from increasingly uncommon progenitor channels. Here we examine a scenario in which massive stars merge after they have both formed a hydrogen-exhausted core. We suggest that this could produce stars that explode as pair-instability supernovae (PISNe) with significantly more hydrogen, at a given metallicity, than in single-star models with the same pre-explosion oxygen-rich core mass. We investigate the subset of those stellar mergers that later produce pulsational PISNe, and estimate that the rate of such post-merger, hydrogen-rich pulsational PISNe could approach a few in a thousand of all core-collapse supernovae. The nature and predicted rate of such hydrogen-rich pulsational PISNe are reminiscent of the very unusual supernova iPTF14hls. For plausible assumptions, PISNe from similar mergers might dominate the rate of PISNe in the local Universe.

Key words: binaries: general – stars: massive – supernovae: general

1. Introduction

The diversity of ways in which massive stars die is heavily affected by the interactions that they undergo during their lifetimes (Podsiadlowski et al. 1992). It is natural to consider binary-star pathways toward all outcomes of massive star evolution, as these stars are typically born in interacting binaries (Sana et al. 2012). Moreover, because the binary-interaction parameter space is large and multi-dimensional, ongoing supernova (SN) discoveries may reveal new diversity arising from novel binary evolution routes. One relatively unexplored question is the influence of binarity on the diversity of pair-instability supernovae (PISNe).

PISNe are predicted to occur in stars with sufficiently massive oxygen–carbon (O/C) cores. In those cores, the temperatures become high enough for photons to produce electron–positron pairs, which results in a decrease of the radiation pressure support and can lead to a dynamical instability. The core then contracts until the temperature is high enough to initiate explosive oxygen fusion (Barkat et al. 1967; Rakavy et al. 1967). If nuclear burning reverses the contraction, this process may result in a single explosion as a PISN, completely disrupting the star.

Models of less-massive stellar cores, with O/C core masses between approximately 28 and 52 $M_{\odot}$,[9] find that they can avoid disruption by the first pulse of explosive burning (Barkat et al. 1967; Woosley 2017). Those stars may experience multiple pair-instability eruptions, collectively called pulsational PISNe, after which there is insufficient nuclear fuel remaining to reverse the next collapse. Pulsational PISNe have been proposed as being responsible for a possible limit to the masses of black holes so far detected by gravitational wave detections (The LIGO Scientific Collaboration et al. 2018), and as explanations for some very luminous SNe (Woosley et al. 2007), but there has been no unambiguous identification of such a pair-instability driven stellar death.

Most newly observed SNe fit within existing classes, but iPTF14hls (Arcavi et al. 2017) is an extraordinary exception. The inferred bolometric luminosity stayed above 10^{42} erg s^{-1} for over 600 rest-frame days, a duration more than 6 times longer than that of a canonical SN, and the light curve during this time displayed at least five peaks. This is different from the single plateaus seen in other hydrogen-rich Type II-P SNe to which iPTF14hls is spectroscopically similar (Arcavi et al. 2017). The total energy radiated during those 600 days was a couple of times 10^{50} erg, well above the energy inferred for any previously known Type II-P SNe. After 600 days, iPTF14hls remained more luminous than a typical SN II-P at peak luminosity. The multiple-peaked light curve is somewhat reminiscent of a pulsational PISN (Barkat et al. 1967; Woosley 2017). However, one challenge with interpreting iPTF14hls as a pulsational PISN is that single stars sufficiently massive to produce luminous pulsational PISNe at metallicities similar to that of the apparent host galaxy of iPTF14hls are typically expected to retain too little hydrogen by the time of the explosion to produce the observed hydrogen-rich iPTF14hls (Arcavi et al. 2017; Woosley 2018).

Here we investigate whether a class of stellar mergers could produce stars that later explode in a hydrogen-rich pulsational PISN. In this model, two stars in a binary system merge to form the SN progenitor after the end of the relatively long phase of hydrogen fusion in each of their cores (Justham et al. 2014). A merger during this evolutionary stage is natural, due to the

[9] This range is found for pure helium cores in Woosley (2017). Different assumptions lead to different ranges, e.g., Chatzopoulos & Wheeler (2012a).

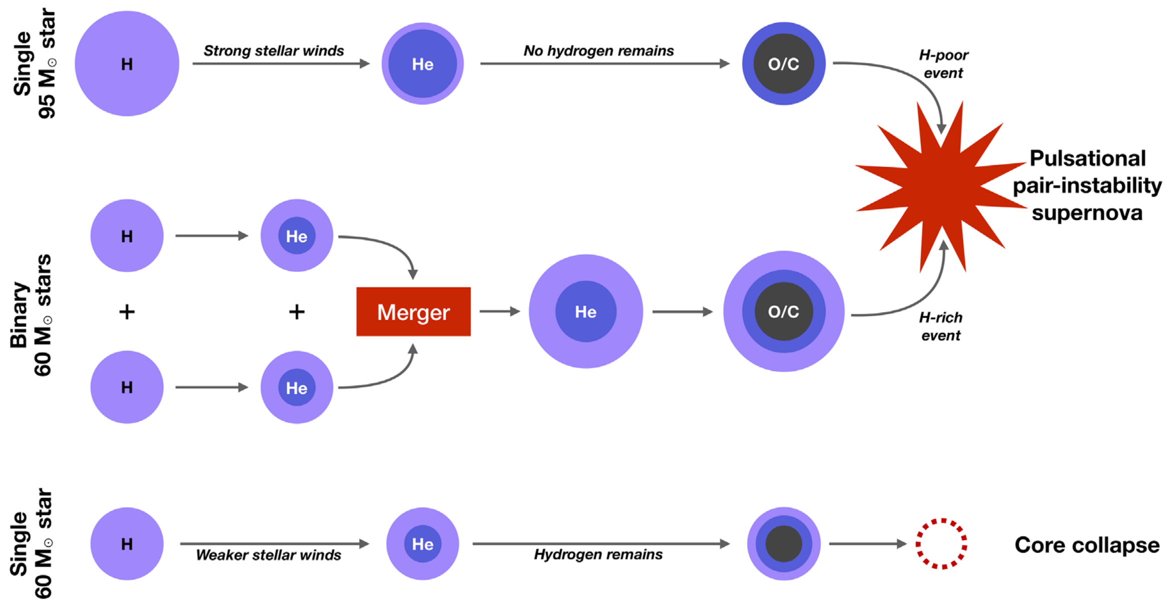

Figure 1. Schematic representation of three possible outcomes of stellar evolution. Top: single stellar evolution of a 95 $M_{\odot}$ star leading to a canonical pulsational PISN. Middle: merger scenario of two stars of initially 60 $M_{\odot}$ each, as investigated in this Letter; this scenario leads to a hydrogen-rich pulsational PISN. Bottom: single stellar evolution of non-rotating 60 $M_{\odot}$ star, which does not produce an O/C core massive enough to be a pulsational PISN.

expansion of the stars after the end of their core hydrogen fusion, and the pre-merger stars will have experienced significantly less fractional mass loss by winds than a single star of the same total mass and evolutionary state. The merger creates a combined helium core sufficiently massive to lead to a pair-unstable O/C core. Figure 1 displays a schematic representation of a single star leading to a pulsational PISN, as well as this merger formation channel. We find that this progenitor scenario could lead to a more substantial hydrogen-rich envelope at the onset of the explosion than in single-star pulsational PISN models with otherwise identical assumptions. We estimate that this evolutionary route could well be significant in producing pulsational PISNe in the local Universe.

2. Massive Stellar Mergers

2.1. Astrophysical Case

Two similarly massive stars transferring mass at an appropriate orbital separation can merge. When both stars are expanding after their main sequence (MS), mass transfer can cause the accreting star to also overfill its Roche lobe. Subsequent loss of mass and angular momentum from one or both of the outer Lagrangian points can cause runaway shrinking of the binary orbit. For such stars, it appears likely that this situation would at least sometimes, and perhaps typically, lead to a merger (see, e.g., Pasquali et al. 2000; Podsiadlowski 2010; Justham et al. 2014).

Cases in which unstable mass transfer occurs when two similar-mass stars have completed their MS, but successful common-envelope ejection prevents a merger, have been proposed as a pathway to explain the formation of some double-neutron-star binaries (Brown 1995; Dewi et al. 2006) and low-mass binary systems (Justham et al. 2011). Those cases typically require binary components with initial masses that are similar to within, at most, a few per cent. However, at higher masses the probability for two stars to interact during the post-MS evolution of both stars becomes larger. This is because the duration of the MS becomes a very shallow function of initial mass (see, e.g., Brott et al. 2011). Hence stars from a wider relative range in mass can simultaneously be between the end of core hydrogen fusion and the start of core oxygen fusion, which is ideal for mergers in our scenario. (Such systems with similar masses and appropriate orbital periods have been observed, e.g., R139/VFTS 527, for which see Section 3.)

Figure 2 illustrates two dimensions of the parameter space for (pulsational) PISNe arising from non-interacting single stars and merger products.

To investigate the subsequent evolution of such a merger product, we model a case with two identical merging stars, each 60 $M_{\odot}$ at zero-age main sequence (ZAMS). For a given primary-star mass, an equal-mass case should be the least favorable for retaining hydrogen, as the total fractional core mass at the time of merger will be higher than in cases with non-equal masses; i.e., the fraction of mass in hydrogen at the time of the merger is the lowest. Less-massive secondary stars would also retain a larger fraction of their H envelope before the merger because of their reduced stellar winds.

2.2. Numerical Modeling

The merger of two stars is complex. Realistic simulations of such events and their outcome are still beyond our reach. However, by making reasonable simplifying assumptions, it is possible to study the properties of the products that are the likely outcome of such mergers. We model a single star and a merger product using Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2010, 2013, 2015, 2018; version 10108). We adopt the same assumptions for the single and merger models, unless stated otherwise. We use the `mesa_67.net` nuclear network, and assume a metallicity of 0.0035, representative of star-forming regions in the Small Magellanic Cloud (SMC), corresponding to [Fe/H] ≈ -0.76 ([Z/H] = [Fe/H] adopting solar-scaled abundances as specified in Choi et al. 2016). For wind mass loss, we use the

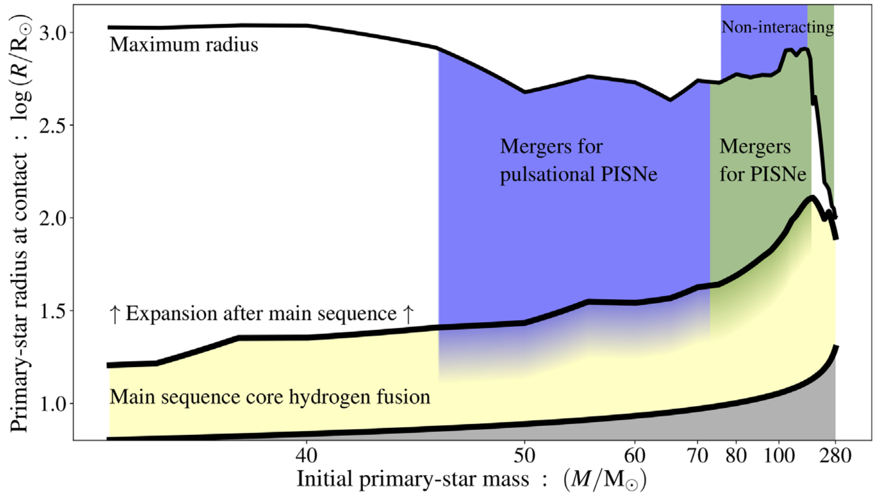

Figure 2. Depiction of the parameter space that is expected to lead to PISNe, including pulsational PISNe. The figure shows stellar radii as a function of initial mass. Primary stars evolve vertically upward in this plot as they expand, and will interact with a companion if they overflow their Roche lobe. The shaded regions indicate where pulsational (blue) and normal (green) PISNe may be produced. For non-interacting binaries or single stars, this is based on the helium core mass range (Woosley 2017). For post-MS binary mergers, the extremes of the shaded regions assume equal-mass mergers. The shading extends to lower radii to indicate a possible contribution from binaries that start mass transfer on the MS. The scalings along both axes are chosen such that equal areas represent equal number density. Stellar radii and helium core masses for this figure are taken from the MIST library of Modules for Experiments in Stellar Astrophysics (MESA) models (Choi et al. 2016) for non-rotating models with an initial metallicity of [Fe/ H] = −0.75, similar to the Small Magellanic Cloud (SMC) metallicity of our MESA models.

"Dutch" wind scheme in MESA (Glebbeek et al. 2009), reduced by multiplication with a factor of 0.3 (Puls et al. 2008; Smith 2014). Cool and hot wind schemes are used for effective temperatures below 10,000 K and above 11,000 K, respectively, interpolating when at intermediate temperatures. For hot winds, the mass-loss rate scales with metallicity as $\dot{M} \propto Z^{0.85}$ (Vink et al. 2001). Convective overshooting extends 0.25 pressure scale heights above convective regions during the MS—specifically until hydrogen is exhausted in the core for the single stars—and until the moment of merger, which happens shortly after the end of the MS in our models.

The ZAMS mass of our single-star model is 95 $M_\odot$, and is 60 $M_\odot$ for each star that we assume to merge. There is significantly more MS mass loss for the 95 $M_\odot$ single star than for the 60 $M_\odot$ pre-merger star (see Figure 3), as expected.

We assume that the structure of the merger product depends on the entropy profile of the merging progenitors, which is consistent with earlier hydrodynamic situations of mergers between less-massive stars (Lombardi et al. 2002) and non-rotating massive star collisions (Glebbeek et al. 2013; although see Gaburov et al. 2008). For equal-mass components, this assumption means that the relative internal composition structure of the merger product is initially the same as that of the progenitor star. Hence we keep the relative internal structure of the pre-merger model fixed while doubling the total mass through relaxation, with no abundance change due to nuclear burning during the merger, and with no additional mixing. However, the thermal structure then readjusts in response to the new hydrostatic balance, which can lead to mixing. Our models are non-rotating and spherically symmetric, but the strong molecular-weight gradients likely suppress rotational mixing (see, e.g., Justham et al. 2014, and references therein). We do not remove mass on a dynamical timescale during the merger, as might be expected, but ≈7% of the post-merger mass is removed by intense winds during the first ≈20 kyr after the merger (just visible in Figure 3), during the time when the model merger product is relaxing toward gravothermal equilibrium. Simulations of head-on mergers between two 40 $M_\odot$ stars at and just after the end of the MS found mass loss of ≈8% (Glebbeek et al. 2013). The amount of mass loss is probably the main uncertainty in our predictions for hydrogen-rich pulsational PISNe. This uncertainty affects hydrogen retention, and so whether our merger scenario would produce hydrogen-rich explosions.

We model the post-merger evolution with the same assumptions as for the single-star model. Figure 3 shows the stellar structures during these evolutionary phases for both models. These models were chosen so that the O/C core masses are very similar at the onset of pair instability, but the post-merger model retains a massive hydrogen-rich envelope. The dominant composition structures of these models, just before the onset of the first pulsation, are shown in Figure 4. The single-star model has a 6.0 $M_\odot$ helium envelope and less than 10^{-2} $M_\odot$ of hydrogen, while the post-merger model retains a hydrogen-rich envelope with 19.0 $M_\odot$ of helium and 9.8 $M_\odot$ of hydrogen.

2.3. Rate Estimates

We estimate the hydrogen-rich pulsational PISN rate, $\mathcal{R}$, as a ratio between the number of pulsational PISNe from mergers in our scenario, $N_{\rm PPISN,mergers}$, and the total number of core-collapse supernovae (CCSNe), $N_{\rm CCSN}$, for a fixed amount of star formation:

$$\mathcal{R} = \frac{N_{\rm PPISN,mergers}}{N_{\rm CCSN}} = f_{\rm binarity} \times f_{\rm primary} \times f_{\rm secondary} \times f_{\rm separation}. \quad (1)$$

The factor $f_{\rm binarity}$ describes the fraction of massive stellar systems that contain close binaries; we assume it to be $f_{\rm binarity} = 0.7$ (Sana et al. 2012).

The factor $f_{\rm primary}$ represents the ratio between the number of binaries in which the initially more-massive star is in the correct mass range to produce a pulsational PISN if a suitable post-MS merger occurs, and the number of stars with the right mass to undergo a CCSN.

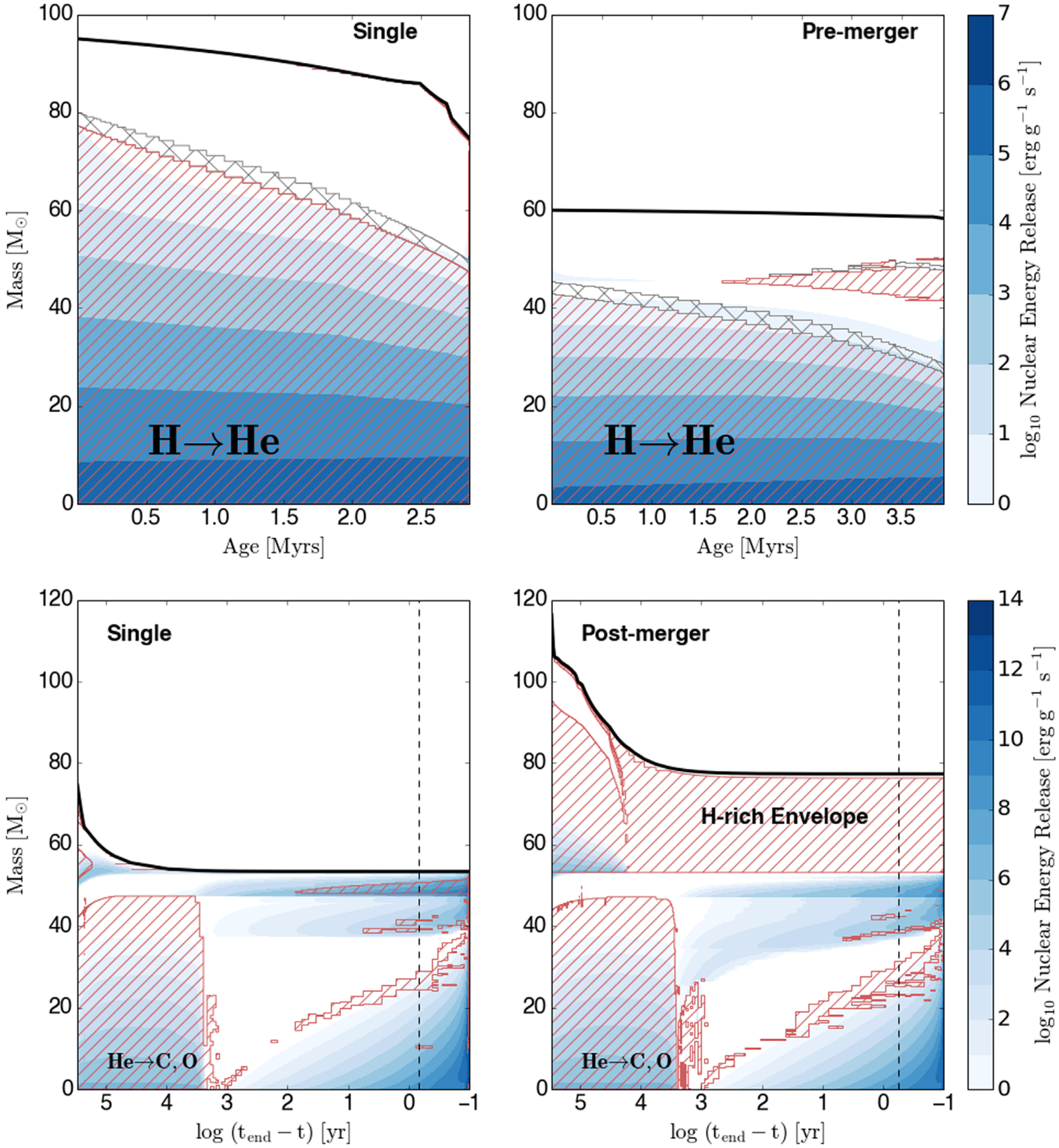

Figure 3. Structures of the single (left) and merger (right) models described in the text. Both MS (top) and post-MS or post-merger (bottom) evolution are shown. The total mass of each star is shown with a thick solid black curve, nuclear burning regions in shaded blue and convective regions in hatched red. For the post-MS models, the vertical dashed lines (black) show when the central temperature reaches $T_c \approx 10^9$ K.

We assume that stars with ZAMS masses in the range [8, 40] $M_\odot$ undergo CCSNe, and use the Salpeter (1955) initial mass function $p(m) \propto m^{-2.3}$.

We estimate $f_{\rm primary}$ using terminal-age MS helium core masses calculated with MESA. We double those core masses to give notional post-merger core masses, and compare those to the range from Woosley (2017). This gives a primary mass range [40, 64] $M_\odot$. As a pessimistic alternative, we only allow the primary to be within [56, 64] $M_\odot$, with mass ranges symmetric about our calculated example merger model. These assumptions lead to $f_{\rm primary} \in [0.01, 0.06]$.

The factor $f_{\rm secondary}$ is the fraction of binaries with a suitable primary in which the lighter companion is sufficiently massive for our merger scenario.

As a pessimistic assumption we include only mergers between components with nearly equal masses, $q = m_{\rm secondary}/m_{\rm primary} \geqslant 0.99$ at ZAMS. For the more optimistic assumption, we consider that mergers between two stars that have both evolved beyond the MS can yield pulsational PISN progenitors. For massive stars, the luminosity–mass relation flattens out and evolutionary timescales vary slowly with mass (Brott et al. 2011; Köhler et al. 2015). This leads to a threshold $q \geqslant 1 + f_{\rm postMS}(\tau/M)(dM/d\tau) \approx 0.85$, where τ is the MS lifetime (Farr & Mandel 2018) and $f_{\rm postMS} \approx 0.1$ is the fraction of time the star spends beyond the MS. These assumptions lead to $f_{\rm secondary} \in [0.01, 0.15]$.

Finally, $f_{\rm separation}$ accounts for the fraction of otherwise suitable binary stars with the appropriate separation to merge in the correct evolutionary phase.

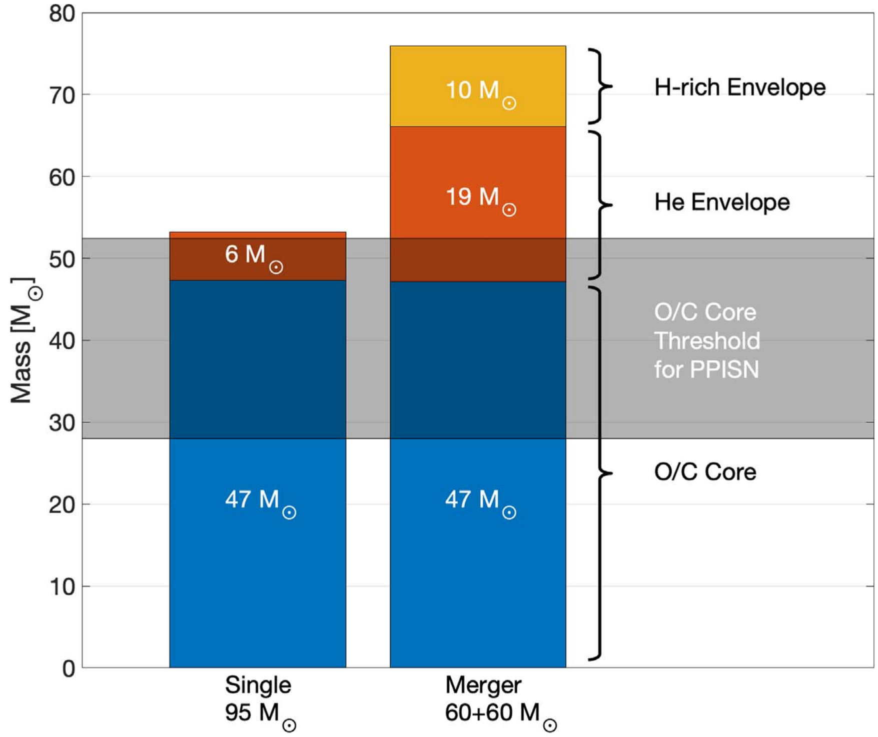

Figure 4. Schematic diagram of the dominant compositions of our single (left) and post-merger (right) models at the moment when the central temperature $T_c \approx 10^9$ K, less than a year before the first pair-instability driven outburst. The bottom (blue) represents the O/C core, while the middle (red) and top (yellow) show the masses of helium and hydrogen outside the O/C core. The gray shaded region represents the range of masses of O/C cores leading to pulsational PISNe according to Woosley (2017): $28 \leqslant M/M_\odot \leqslant 52$. Both cases are expected to lead to a pulsational PISN, but the single-star model has less than 0.01 $M_\odot$ of hydrogen at explosion, while the merger model has approximately 10 $M_\odot$.

We assume the flat-in-the-log distribution of initial separations $p(a) \propto a^{-1}$ (consistent with, e.g., Sana et al. 2012). Depending on whether we require the merger to happen while the primary star is close to the end of the MS—within a factor of two in radius—or optimistically allow for mergers at any point until the star's maximum radial expansion ($\approx$800 $R_\odot$), we find that $f_{\rm separation}$ falls in the range [0.13, 0.46].

These assumptions predict a range of rates of suitable mergers leading to pulsational PISNe that goes from $\mathcal{R}_{\rm min} = 1.3 \times 10^{-5}$ CCSN^{-1} for conservative assumptions to $\mathcal{R}_{\rm max} = 3.2 \times 10^{-3}$ CCSN^{-1} for more optimistic ones. Empirical estimates indicate that events such as iPTF14hls could constitute about 10^{-3}–10^{-2} of the SN II rate (Arcavi et al. 2017), where Type II-P SNe make up $\approx$70% of all CCSNe (Shivvers et al. 2017).

Our rate estimate does not include a potentially significant contribution of stellar mergers from binaries with initially closer separations. These massive overcontact binaries (Marchant et al. 2016) may experience several mass-transfer episodes during the MS, which could lead the stars to approach terminal-age MS at the same time. Our rate estimates are also sensitive to mass-loss-rate prescriptions, which are in turn a function of metallicity. Metallicity-dependent stellar winds reduce both the size of the core and the amount of hydrogen retained in the envelope at the onset of a pulsational PISN. Furthermore, radial expansion, which determines the range of binary separations for which suitable mergers can occur, is also a function of mass and metallicity. We generally expect lower-metallicity environments to yield a higher rate of hydrogen-rich pulsational PISNe. Their total rate in the local Universe is an integral over all metallicities at which star formation occurs.

3. Discussion and Conclusions

The R139 binary in the Tarantula nebula in the Large Magellanic Cloud (LMC), also known as VFTS 527, consists of two very similar supergiant Of stars of about 60 $M_\odot$ and an orbital period of about 150 days (see Taylor et al. 2011; Almeida et al. 2017). This is a near-perfect example for our scenario. Apart from the metallicity, this system is a real-world illustration that systems exist that may follow the merger scenario that we have described. Another well-studied close analog is WR20a, containing two stars each of 82 $M_\odot$ (Bonanos et al. 2004; Rauw et al. 2004, 2005), which would be an excellent candidate for a future binary-merger progenitor of a PISN if the orbit were slightly wider.

This merger route is not the only way to potentially increase the rate of pulsational and non-pulsational PISNe. Rotational mixing increases the core mass of stars with a given initial mass, which may allow initially less-massive stars to reach the pair-unstable regime, although with less hydrogen in their envelope than for stars of the same mass when evolving without rotational mixing (Langer et al. 2007; de Mink et al. 2009; Chatzopoulos & Wheeler 2012a, 2012b; Marchant et al. 2017). Runaway mergers of massive stars in stellar clusters have also been discussed as potential progenitors of PISNe (Portegies Zwart & van den Heuvel 2007; Glebbeek et al. 2009); however, this is not obviously more likely to lead to hydrogen-rich progenitors at the time of the PISN than for single stars.

An intriguing question remains whether iPTF14hls represents a case for a hydrogen-rich PISN resulting from the scenario explored here. While the metallicity of our models is below the estimated range of $\approx$0.4–0.9 $Z_\odot$ for the host galaxy of iPTF14hls (Arcavi et al. 2017), uncertainties in the metallicity estimate for the progenitor star are significant. We do not claim that this evolutionary scenario has explained all of the specific features observed or inferred for the iPTF14hls transient (see, e.g., Arcavi et al. 2017; Woosley 2017), but we consider that the possibility is worth further modeling and investigation. Other models, including circumstellar material interaction in a regular CCSN and events powered by the spin-down of a magnetar, have not fully explained iPTF14hls (Dessart 2018; Woosley 2018).

There is tentative observational evidence for an eruption at the location of iPTF14hls 50 yr previously (Minkowski & Abell 1963). If this was an earlier pulse related to iPTF14hls, it may be challenging for the simpler pulsational PISN to explain it, as much of the hydrogen would likely be expelled during that early pulsation. One very speculative alternative is that this earlier optical transient was related to an extremely late merger, in which case iPTF14hls would be following a very fine-tuned scenario.

Another unusual event that has been discussed as a possible pulsational PISN is SN 2009ip (Fraser et al. 2013; Pastorello et al. 2013), with progenitor metallicity similar to that of the SMC (Pastorello et al. 2013). It may be interesting to reconsider whether this event, originating from a luminous blue variable star, may also have been a hydrogen-rich pulsational PISN from a merger product.

Our scenario does not only produce a pathway for some hydrogen-rich pulsational PISNe, it also increases the range of initial stellar masses and metallicities from which PISNe can originate, whether hydrogen-rich or not. PISNe from mergers may even dominate the PISN rate in the local Universe if stellar winds are sufficiently high to suppress PISN production at even moderate metallicities in single stars. This formation channel may therefore have significant consequences for the chemical yields from PISNe. A strong nucleosynthetic signature of enrichment by PISNe had been expected in low-metallicity stars, but searches for that abundance pattern have had limited success (see, e.g., Nomoto et al. 2013). However, increasing the rate of PISNe at high metallicity would not exacerbate this problem, because the distinctive PISN elemental abundance pattern would be damped when a PISN enriches gas that has already been enriched by previous generations of regular supernovae. The new age of wide-field transient surveys is already producing unexpected discoveries, as shown by iPTF14hls. The ongoing development of such surveys should provide further examples of similar events with which to test our proposal.

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Software: MESA (Paxton et al. 2010, 2013, 2015, 2018), mKipp (doi:10.5281/zenodo.2602098), MESA inlists (doi:10.5281/zenodo.2644593).

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